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BEPPS-GSCAPPP: Generative system of computer aided process planning for prismatic components

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BEPPS-GSCAPPP

Generative System of Computer Aided Process Planning

for Prismatic Components

Submitted by

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Summary

Process planning is the process which determines the method and sequence of machining a workpiece to produce a finished part or component to the design specification. Traditionally, process plans are generated manually by an expert planner who has experience of shop floor operations. Under batch production conditions, where lead time is critical, computer integration is difficult to achieve with manual process planning. Therefore, to increase productivity, competitiveness and integration many manufacturing industries have invested in automating process planning activities. Computer-Aided Process Planning (CAPP) has not only been shown to give an increase in planning productivity, but also gives more accurate results and produces more reliable plans.

This work presents a generative CAPP system, BEPPS-GSCAPPP which is aimed at automatically generating process plans for prismatic components on conventional machine tools in a batch manufacturing environment. The system contains three stages: interactive stage, automatic stage and output stage.

The interactive stage provides the system with the information required for process planning. It is input via computer prompts and is then kept in a separate file in the computer data base.

The automatic stage is designed with a modular structure. It contains 8 modules that automatically execute a range of planning activities namely: raw material selection, feature ordering, operation sequencing, machine tool selection, cutting tool selection, cutting condition selection, total time calculation and workpiece

holding device consideration. Each module extracts relevant information from the data base files via a computer program and uses rules and logic to generate particular process planning decisions. The raw materials selection module chooses the most appropriate stock size available. A feature ordering routine has been devised to order features automatically with reference to a basic score given to each feature.

During the output stage the system automatically produces a process planning sheet which details all the necessary information needed by the shop floor.

The system also contains knowledge and database information which includes a substantial amount of information that has been elicited, refined and structured into separate files. Rules and logic that have been derived from different sources are formalised and included within the system modules.

The results of prismatic components that have been planned using this system compare favourably with plans provided by various companies in the U.K.

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Nomenclature

BROU	: Basic Roughness.
BTOL	: Basic Tolerance.
BTF	: Boring Tool File.
CAD-TRA	: CAD Translator File.
CUT-TO-LEN	: Cut-To-Length Module.
CCTF	: Cylindrical Cutting Tool File.
CMTF	: Cylindrical Machine Tool File.
DTF	: Drilling Tool File.
GTF	: Grinding Tool File.
HMCTF	: Horizontal Miller Cutting Tool File.
HPM	: Horizontal Partition Method.
MPM	: Mixed Partition Method
NCX-SEC	: Non-Constant Cross Section.
PCX-SEC	: Partially Constant Cross Section.
RUF-AND-FC	: Rough and Finish Cylindrical.
RUF-AND-FF	: Rough and Finish Flat.
SCORE	: Scoring Technique.
SCTF	: Surface Cutting Tool File.
SGCTF	: Surface Grinder Cutting Tool File.
SMTF	: Surface Machine Tool File.
TOP-TO-BOT	: Top-To-Bottom Technique.
TCX-SEC	: Totally Constant Cross Section.
VMCTF	: Vertical Miller Cutting Tool File.
VPM	: Vertical Partition Method.

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Chapter (1)

Introduction

1.1 Computer Integrated Manufacturing Systems

The manufacturing factories of today are faced with dramatic fast changes due to greater worldwide competition, advancing technology and a greater tendency towards product variety that leads to a higher incidence of batch manufacturing. Companies need to react to changes much faster and in a more flexible way than in the past. They need to make correct decisions in a very short time, optimise information flow, create effective manufacturing systems and increase design productivity. To achieve this much research and application has been aimed at integrating all activities in a way that leads to efficient and radical change. This move towards integration is now widely known as *"Computer Integrated Manufacturing"* [1,33,37].

Computer Integrated Manufacturing (CIM) is described by Scheer [69], as being concerned with the integrated information-processing requirements for the technical and operational tasks of industry. The operational tasks are often referred to as the production planning and control (PPC) functions and include: cost estimating, materials management, operational data collection and so on. The technical activities include: Computer-Aided Design (CAD), Computer-Aided Process Planning (CAPP), Computer-Aided Manufacturing (CAM), Computer-Aided Quality Control (CAQC), and Maintenance.

To design a CIM system, it is necessary to have design methods. The methods must rely on a conceptual model in order to take into account the close interconnection between the product, facility and management [64,6,33]. There is also a need to create designs which are suitable for manufacturing and this requires that the functions of process planning and-in the course of design, cost estimating are also included in the CIM model [69].

As discussed above, CIM deals with the fundamental effect on manufacturing industry of integrating manufacturing activities and facilities using computers. The computers used in manufacturing not only contribute to decision making, but also directly control much of the production equipment. To gain maximum benefit out of computer integration, the decision maker should have access to all the data on all relevant computers together with the use of computers to analyse the data [79,76]. Although computers have been used intensively in most manufacturing activities this has been without any sort of integration. The only superficial and notable integration is that between CAD and CAM. The CAD/CAM systems developed during the 1970s and early 1980s were designed primarily to address engineering problems [34]. With CAD/CAM, a direct link is established between product design and manufacturing engineering. The goal of CAD/CAM is not only to automate certain phases of design and certain phases of manufacturing, but also to automate the transition from design to manufacturing within Computer Integrated Manufacturing Systems [33,43,6,47,63]. This kind of linkage between CAD and CAM cannot take place without passing through an important bridge between them: Computer-Aided Process Planning (CAPP).

Although the research reported in this thesis is aimed at providing knowledge towards the full automation of process planning, it is important to understand other CIM components, particularly PPC, CAD and CAM. These together with an overview of CAPP are presented in the following sections.

1.1.1 Production Planning and Control (PPC)

PPC is usually involved with both manufacturing planning and manufacturing control. It has been discussed in different references under different names such as: "*manufacturing control*" by Ploss [61], "*factory management project*" [16] and "*manufacturing resource planning*" by Wright [81]. All these terms refer to computerised information systems designed to integrate the various functions of production planning and control. These functions involve organising the purchase of raw material and the start of the various production processes so as to meet delivery dates. They also involve making allowances for all those unpredictable elements which can cause chaos even to the best planned activities. **Figure 1.1** presents a block diagram illustrating the functions and their relationships in a Computer Integrated Production Management System (CIPMS) [35]. Primary data management within a computerised production planning and control system makes available the source data necessary for the planning of materials and capacity management. At the same time it yields the data needed for the production plan for a specific production order, which is the basis of production control. The production plan contains the essential information needed for production [69,64,35].

1.1.2 Computer-Aided Design (CAD)

Computer-Aided Design (CAD) is defined [34,64,35,73] as any design activity that involves the effective use of the computer to create, modify or document an engineering design. CAD is most commonly associated with the use of an interactive computer graphics system referred to as a CAD system. The use of CAD system technology for the design process increases productivity because it shortens the time for the development phases of a product. A CAD system contains hardware and software which are effectively integrated into one system. The CAD hardware typically includes the computer, graphics display terminal, keyboard and other

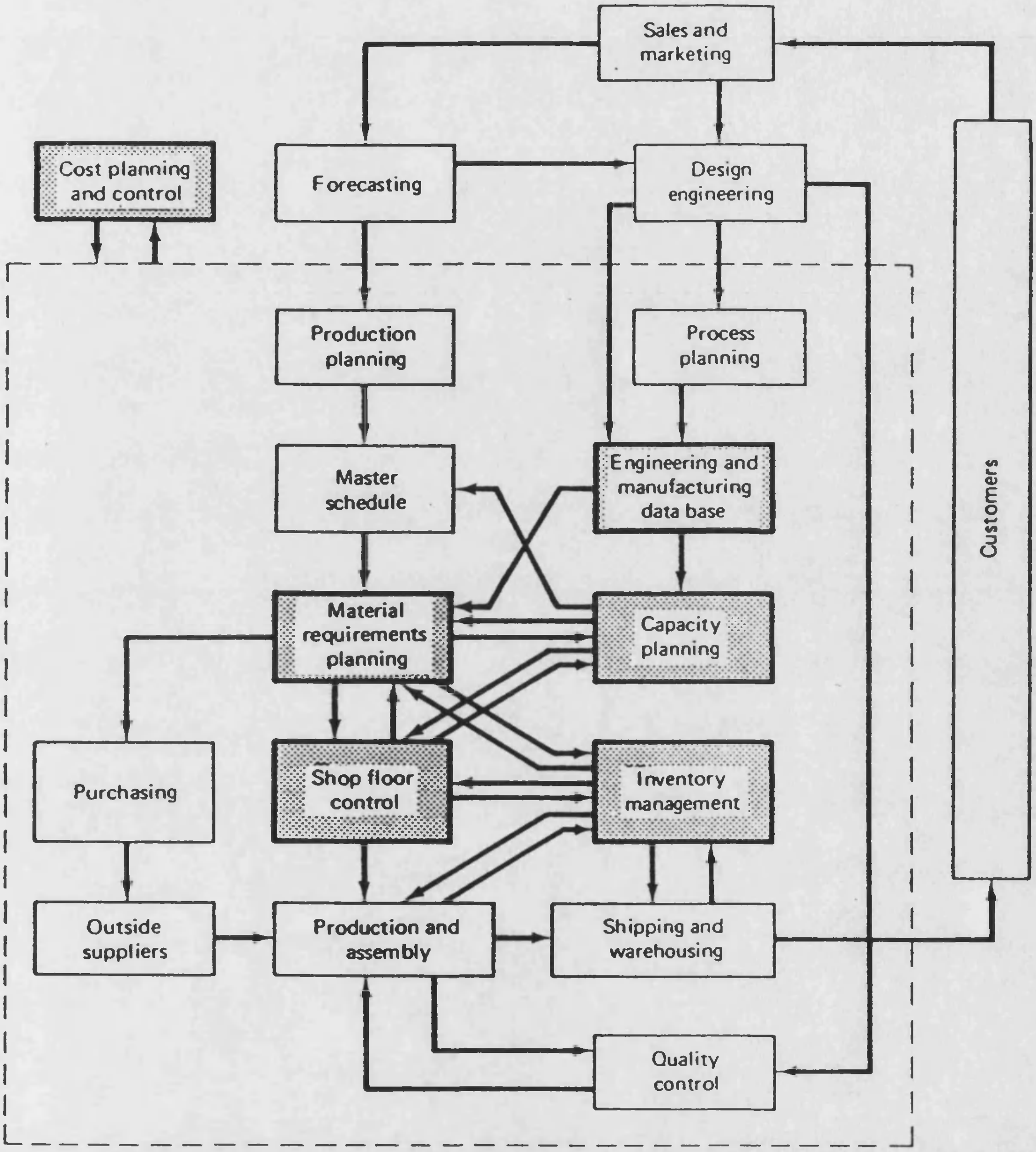


Figure 1.1: CIPMS Functions in a Computer Integrated Production Management system [After CAD/CAM by Groover and Zimmers].

peripheral equipment. The software consists of the computer programs to implement computer graphics on the system plus application programs to facilitate the engineering functions of the user. The characteristics of a CAD system as represented by Rembold and Dillmann [64] are shown in **Figure 1.2.**

1.1.3 Computer-Aided Manufacturing (CAM)

Computer-Aided Manufacturing (CAM) is defined as the effective use of computer technology in the planning, management, and control of the manufacturing function [34,35]. Its application can be divided into two categories [34]:

- Manufacturing planning.
- Manufacturing control.

In manufacturing planning, CAM applications use the computer indirectly to support the production function without any direct connection between the computer and the process. Some of the applications of this category are: cost estimating, computer-aided process planning, computerised machinability and data systems, and computer assisted NC part programming.

Manufacturing control is concerned with developing computer systems for carrying out the manufacturing control function: i.e. managing the physical operations in the factory. Process control, quality control, shop floor control, and process monitoring are all included within the scope of this function.

It is clear from the definitions of CAD and CAM that it is difficult to integrate those two functions without process planning being involved. Particularly in CAM,

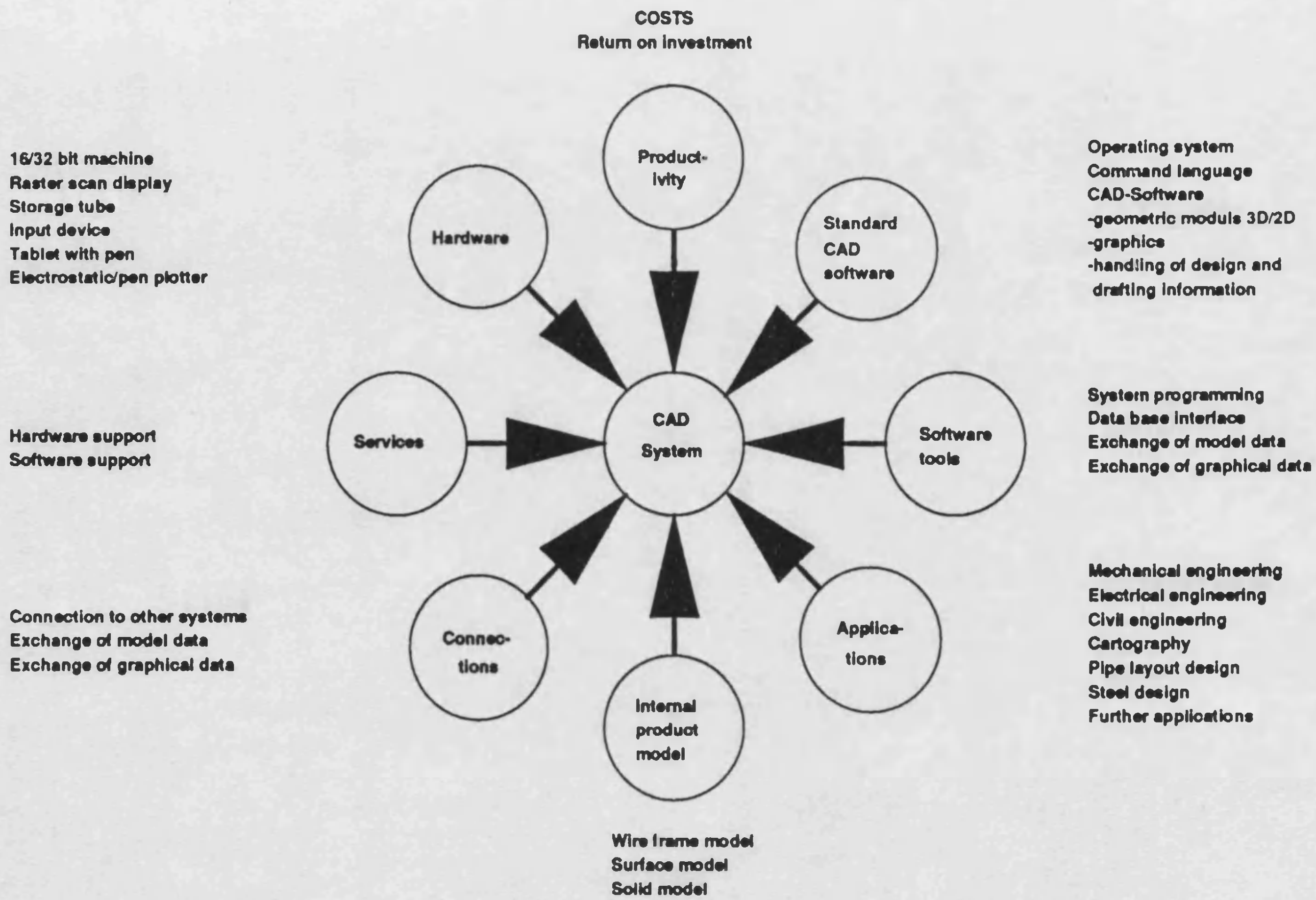


Figure 1.2 Characteristics of CAD systems [After Rembold and Dillmann].

information cannot be effectively transferred from CAD to CAM unless it passes through a computer-aided process planning system. Therefore CAPP can be considered as an important linkage between CAD and CAM in manufacturing.

1.1.4 Computer-Aided Process Planning (CAPP)

Process planning, the activity linking CAD and CAM, is the least advanced element in the CIM environment [50]. It plans the transformation of production parts from their raw material to their finished state according to the design specification. Also it is defined as the bridge between the design and manufacture of components [34,35,73]. It is concerned with determining the methods and their sequence required to produce a given part. The methods and their sequence are documented on a form called a "*procedure sheet*" which details the results of various decisions that are required in order to manufacture the part. These decisions include:

- Selection of processes.
- Sequencing the processes.
- Selection of the machine tool set.
- Selection of cutting tools.
- Calculation of machining variables.
- Selection of workpiece holding devices.
- Identification of non-machining elements.
- Cost estimation.

Traditionally process plans are generated manually and are documented on route sheets that specify both the processes and the machines to be used. This function is usually carried out by an expert planner who is highly skilled in the decision making aspects of process planning and has a good experience of shop floor operations. Many of the tasks performed by the planner requires expert knowledge and experience in both design and manufacture. The decision-making process in process planning is thus very complex [26]. There are a number of disadvantages to manual process planning, the major one being inconsistency [79]. It is not unusual for different planners to specify different routes for the same part, each expressing their own preference. Furthermore there is no way of being sure that any route is optimal, and thus the level of planning proficiency will affect the efficiency of manufacturing. The computer offers potential for reducing routine clerical work, and, at the same time, it is capable of calculating complicated formula and analysing logic rules in a much faster time. Process planning systems which are assisted by computer power are called computer-aided process planning (CAPP) systems and have been the subject of much research in recent years.

A CAPP system would provide the opportunity to generate process plans which are rational, consistent, and even optimal [35]. CAPP could help a batch working company to increase productivity by up to 600%, to improve documentation (*better consistency, legibility, and less errors*), and to give more consistent planning [55].

The function of computer-aided process planning is to determine the process plan for a part by computer [10]. The majority of CAPP systems at present are not fully automated and determine the process plans interactively with the planner putting in much of the expert logic. Typically, the commercial and research CAPP systems that have been developed are based on one of the following four approaches [10]:

- *Constructive Approach* in which the information for manufacturing is held in separate menus in the computer database. Typically, the planner has to specify the sequence of operations, machines, cutting tools and materials to be used to produce a component. A menu structure is used to select the relevant screen 'page' from which to choose the appropriate material, machine, cutting tool, and operation. Once the machine type has been selected, the system will often automatically choose appropriate cutting conditions and then calculate the machine time, and finally output the process planning sheet.

- *Variant or Retrieval Approach* creates a process plan for parts which are related to a specific composite part in a computer database. The composite part that contains all the features in a part family is retrieved and modified to suit a new part, and hence a process plan is created. The logic of the variant method is typically based on the Group Technology (GT) method of classification and part coding.

- *Generative Approach* generates a new process plan for a given part from first principles. The system uses information which is available in a manufacturing database. The manufacturing database contains the part description data and technological information such as machining data and tooling information. Using expert process decision logic the computer program manipulates the data in order to automatically generate a process plan.

- *Expert Systems Approach* is a new form of generative process planning that uses an expert system program to make the planning decisions. From a structural point of view an expert system is a knowledge-based inference engine [32,42]. The inference engine is an interpreter for a high level language in which the knowledge base is expressed. The knowledge base is an interconnected set of well-established and documented definitions, facts and rules. The inference engine determines the process plan according to the production rules and resolves any conflict amongst them when several rules are satisfied. Expert planning systems for process planning are currently being researched [53].

1.2 Identified CAPP Problems

As discussed, process planning has been traditionally an art in which expert planners typically create individual plans. In many cases different planners would create different plans for the same component. Marked variations in planning can be seen in industry, particularly from company to company.

A number of both commercial and research CAPP systems have been put forward which have been typically based on either a *"constructive"* or *"variant"* approach together with a level of generative capability. The systems that are partially generative have concentrated, in general, on the automatic selection of the cutting tools and operations required to produce individual component features, in addition to the calculation of the cutting conditions. Most of these CAPP systems have been designed for rotational rather than prismatic parts.

Within CAPP systems for prismatic components the selection of appropriate raw material has not received any significant attention. The notable exception to this was reported in a system called GIPPS [46], in which a raw material selection module has been designed for a specific company and covered a limited range of components.

Prismatic components normally consist of, at least six plane surfaces. In order to identify feature's location on each plane surface, a datum has to be selected. The datum and feature data indicate the cutting direction needed to produce the feature, and therefore can also assist in placing the component in the appropriate position for machining. No CAPP system has been found that claims to construct a framework for selecting an applicable datum for a prismatic component.

Although feature ordering is perhaps the most important element to automate, it has not, as yet, been satisfactorily included in any current prismatic CAPP system. The process plan for a component should not only include the sequence of operations for producing individual features but should also contain the order in which the features are to be processed together with knowledge as to whether features are to be processed individually or in combinations. The shortage of a feature ordering module in existing CAPP systems especially for prismatic components is due to the complex 3-D nature of prismatic parts.

This work presents the conception, design and development of a generative CAPP system (BEPPS-GSCAPPP) for prismatic components, which is designed to significantly add to the knowledge and techniques that are required to overcome many of the weaknesses that are currently present when generating process plans automatically.

1.3 The Research Objectives and Aims

This research is concerned with designing a module of the Bath Expert Process Planning System (BEPPS) which is being prepared at the University of Bath. BEPPS is a generative Computer-Aided Process Planning (CAPP) system that has been designed with a modular structure that includes modules for conventional machines, NC machines, tooling and fixtures, cost estimating and links to both CAD and production management systems.

The primary aim of this work is to develop an automated Generative System of Computer-Aided Process Planning for Prismatic type parts (BEPPS-GSCAPPP) on conventional machine tools, in a batch manufacturing environment. The main objectives of the proposed system are:

- To elicit production rules and factual knowledge from a variety of sources and then represent, and organise them into a knowledge base for process planning.

- To develop an easily used interactive module that allows the input of the general and component information to the system.

- To develop a methodology for identifying the planes edges and surfaces of prismatic components.

- To provide an approach in which the planner has to select the datum for the component.

- To develop a methodology to select the most appropriate size and shape of standard raw material and to identify the most applicable cutting-off operation to be used.

- To develop feature-ordering and operation-sequencing methodologies for simple prismatic shapes.

- To develop a methodology that automatically selects an appropriate machine tool set for the given operations.

- To develop a methodology for selecting appropriate cutting tools and cutting conditions such as speed, feed and depth of cut.

- To design a database that enables process plans to be generated effectively.

- To develop a computer program that generates process planning documentation automatically using the methodologies specified above and the information held in the database.

- To provide a means of easily updating both the databases and rules within the system.

- To develop a file format that can be used as a standard input for the process planning systems and that is capable of recording information interactively from the planner or automatically from CAD.

1.4 Research System Limitations

As the proposed system is initially for research, specific boundaries have been used to limit the database and logic. These boundaries are:

- In terms of raw material, the system considers three of the most common materials used in the batch manufacturing factories for prismatic parts. Those are: Mild Steel, Carbon Steel and Aluminium. Standard shapes and sizes for these materials have also been used rather than castings or forgings.

- The system utilises a number of common component features machined on prismatic parts, namely: Simple Hole, Stepped Hole, Countersink, Face, Pocket and Slot.

- The conventional machine tool set proposed for this system includes the following machines: Pillar Drill, Radial Drill, Vertical Boring Machine, Internal Grinder, Horizontal Mill, Vertical Mill and Surface Grinder.

- The system utilises a specified number of different types of cutting tools with different sizes to match the features and machine tool set in the system.

- The system plans prismatic shapes that contain only vertical or horizontal machined surfaces.

- The workpiece holding devices in this system are considered in outline only.

Chapter (2)

Review of Literature

2.1 Introduction

As described in Chapter 1, process planning is concerned with the preparation of the procedure sheet that contains the processing steps by which the product should be manufactured.

There have been a number of researchers and industrial groups working in the process planning area since the 1950's. The main objective has been to develop a system of computer aids for the manufacturing engineer. Since then several CAPP systems have been developed using one of the four valid approaches that have been defined in Chapter 1. These approaches are; the constructive, the variant, the generative, and the expert systems approaches.

In this chapter, some of the relevant existing CAPP systems for prismatic components are reviewed and discussed.

2.2 Constructive Computer Aided Process Planning Systems

Such systems can be built for different types of manufacturing environment, and have been the most widely used of the CAPP approaches. However they still require an expert planner and also require a significant effort to build and update the system.

Typical commercial CAPP systems using this approach are namely; CAPES [70], LOCAM [52], SOFIE3 [74], and C-PLAN [11].

These systems are similar in structure in that they provide the planner with options at different levels throughout the planning stage and guide the planner in selecting an appropriate option if more than one element is relevant. They also calculate machining times and costs, and store plans for continued use.

2.2.1 LOCAM System

LOCAM [52], was developed to produce detailed process plans. The system's logic depends on recalling pre-stored manufacturing rules and time standards from the database. Standard information for individual operations is stored by the system either as single items or as tables together with their description. A sequence of operations is compiled by the planner to select the appropriate elements from the standard data, and the system then combines them in the manner specified by the planner. The selection of element values depends on parameters which are stored by the program from the information provided by the planner. The system also requires assistance to determine the sequence of operations.

Note: The LOCAM, SOFIE3 and C-PLAN systems claim that they can be operated in a constructive, variant, or generative manner.

2.3 Variant Computer Aided process Planning

In the variant approach, parts are segregated into families formed by considering one of the following [50];

1- Design attributes, such as the geometric shape and overall size.

2- Manufacturing attributes, such as the sequence of processing steps required.

3- A combination of design and manufacturing attributes.

The basis for this approach is part classification which is used to identify each part family. A composite process plan is established by experienced process planners for each family that contains the common characteristics of each family part. These family plans are stored in the computer database to be retrieved and modified later when a new or revised machined family part requires planning.

Figure 2.1 describes the procedure used in the variant process planning systems. The following steps are considered as the basis for a typical variant system:

(1) The user is required to enter the part code number.

(2) A search for an existing part family to match the code number takes place.

(3) If an identical code number exists, then a standard plan is retrieved.

(4) The user examines and modifies the standard process plan.

(5) The final output document is produced.

A number of variant computer-aided process planning systems have been developed. The following section describes ICAPP [24,27] a variant computer-aided process planning system which was developed for prismatic components.

2.3.1 ICAPP System:

ICAPP stands for Interactive Computer Aided Process Planning. It is a system for non-rotational components. It was developed by Eskicioglu [24,26,27] at UMIST in 1981. The ICAPP system is feature-oriented and is designed to plan eight basic machining processes, i.e. drilling, boring, reaming, tapping, counterboring, countersinking, face milling, and peripheral milling. The system was intended to be used for parts produced on conventional drilling, boring, and milling machines as

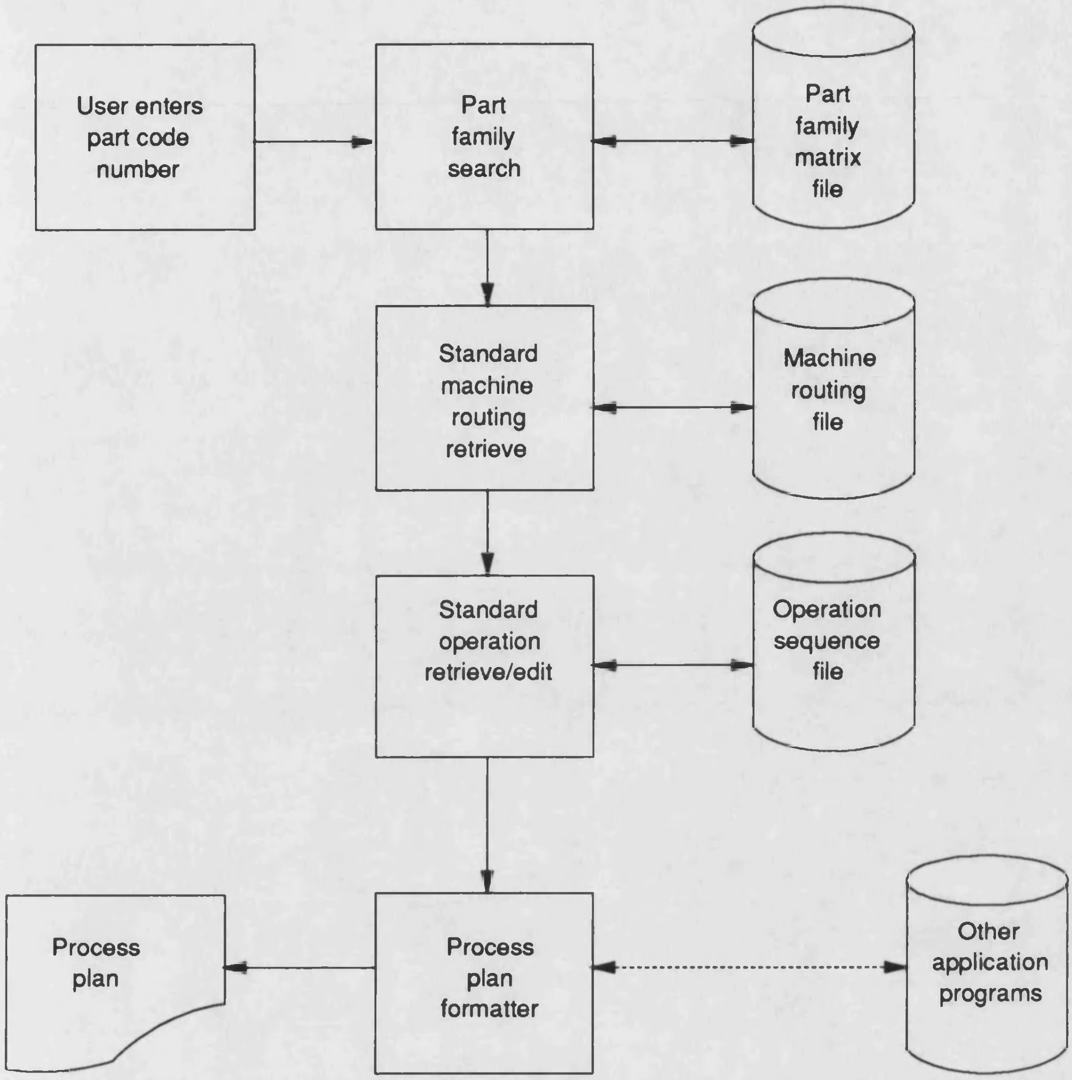


Figure 2.1 Information flow in a retrieval-type computer-aided process planning system (After Groover & Zimmers [35]).

well as machining centres. The necessary machining operations to produce the features are selected by the system with regard to the feature type and it's geometrical and technological attributes.

This system has a modular structure and its logic is a combination of variant and generative planning types. The variant planning data and the generative logic information are kept in a Cutting Technology File (CTF). The application of variant planning takes place via the part family concept (see Section 2.3). Each part family is derived from a composite part. The manufacturing methods of the composite part are determined including the sequence of machining the features and are then stored in the CTF. The system then uses the data in the CTF for each part in the family and processes it accordingly.

The ICAPP input information is collected interactively in three stages:

1. General information.
2. Technical drawing and workpiece information.
3. Process planning information.

After all the input necessary for process planning is completed for each described feature the machining operations and the cutting parameters are selected automatically. At an interactive editing stage, the process planning sheet produced by ICAPP can be modified manually if required.

The ICAPP is limited in its generative ability to schedule the sequence of operations automatically in the general case (except for hole making).

The present state of development has enabled component designs generated on a computervision CAD system to be transmitted and re-displayed via an Initial Graphics Exchange Specification (IGES) link to ICAPP [18,77].

2.4 Generative Computer Aided Process Planning

Generative process planning involves the use of the computer to create individual process plans from first principles, automatically and without human assistance [12,34,35]. In this approach, the parts can also be grouped into part families [80], but a rigourous analysis is made for each part family to determine what features of the part require which operations. This results in the process planning logic for the part family, which is stored as a decision rules. When a new part requires planning, it first must be analysed to determine what features, incorporated in the decision logic, are present on the part. The decision model is retrieved and an operation sequence is generated by processing the decision model with the part features. Essentially, the computer executes the thought process of the planner.

In the variant process planning approach, the process plan is retrieved by sorting standard process plans, but in generative process planning the system has its own knowledge-base which consists of a manufacturing database and decision logic that imitates the process planner.

There are three basic ingredients required to generate a process plan in a generative CAPP system [12,34], these are; a part description, decision making logic and information databases.

2.4.1 Part description

The description of the part contains all of the data and information required to generate the process plan. This information includes both the geometric and the technological data. Most of the existing CAPP systems input part information interactively from the planner.

Since manufacturing logic is highly variable from company to company according to their manufacturing facility, many different input methods have been used to input the part description into the generative CAPP systems;

(a) Code Description: Coding systems are used in manufacturing to facilitate retrieval for design and manufacturing purposes. In process plan generation, most existing techniques for part description are based on Group Technology (GT) [31,58,75]. The parts are grouped into families based on feature or process characteristics. Each part in a family, in spite of their differences in shape, has the same code.

This methodology is first used in the variant CAPP system using GT. The code number of the part can define the part features in significant detail. Also it identifies a component's design specification and/or its manufacturing attributes. Some generative CAPP systems also use coding systems to input part or surface information.

The benefit of using this method is that, it reduces significantly computing time because it is relatively easy to generate and manipulate the code. Despite the advantage of this scheme, the suppression of differences among the parts within a family, in a group coding scheme, makes the scheme inadequate for the generation of efficient process plans [2]. Therefore, a human interface is needed between design and the process planning function to overcome this problem.

Several generative CAPP systems use this method to describe parts, for example APPAS [82].

(b) Descriptive Languages: Some CAPP systems have developed introduced special languages to describe parts directly for the process planning function. These descriptive languages are written in a special format that enables the geometric and technological information to be introduced into the system. This method has been shown to give a high performance, especially for CAPP systems that use the expert system approach.

GARI [21] is a typical example of a generative process planning system for prismatic parts which uses this scheme. The shape of a part is described to GARI as a basic volume (e.g. Cylinder etc.) together with a specification of the feature types used in the drawing (e.g. hole, face, etc.). Dimensions and tolerances are input as given on the drawing.

Descriptive language is easy to formulate and understand for simple components, but for complex components a lot of effort is required to describe a component to the system. Also this scheme must still be carried out manually.

(c) CAD Interface: CAD is concerned with the use of the computer to support the design functions, and CAM is concerned with the use of the computer to support manufacturing activities [34]. The potential of CAD/CAM cannot be realised without a method for integration. The integration of CAD with CAM requires the generation of manufacturing data from design data. Since process planning converts design specification into manufacturing instructions, it has been recognized as having a key role to play in the integration of CAD and CAM [20].

Some researchers have started to form a direct link between CAD and CAPP systems, to eliminate any human interruption, by using special format to convert the CAD output data into a neutral format file to be used directly as process planning input data. Since the product model may be produced on a wide variety of CAD systems, some common format of product model transfer is required.

IGES, SET [60], VDA-FS [69] and DXF were developed in the United States, France, Germany and United States respectively, and they are regarded as national standards for data exchange. Among these four standard IGES is perhaps the most widely used specification for CAD/CAM data exchange. IGES is used in the ICAPP [25] system for prismatic components. Vosniakos and Davies [77] described an IGES post-processor for interfacing CAD and CAPP for $2\frac{1}{2}D$ prismatic components using a wire-frame modeller to represent the parts. This interface however, instead of providing both geometric and technological data, only provides geometric entities in ICAPP. In addition to this problem, IGES cannot at present deal with 3-D solid modelling [77].

So far, there has not been any system that can automatically transfer both the geometric and technological data directly from CAD to CAPP for prismatic components. Therefore, a complete CAD model that can exchange all component data to CAPP systems is desperately needed to enable comprehensive integration.

2.4.2 Decision Making and Logic

Decision logic is the most important element in a generative CAPP system. It plays the role of directing the flow of the program and manipulates the data in the database. Two stages can be identified: (1) to computerise judgment type decisions which are currently taken by people; (2) to manage the increased complexity of those decisions when much more data is available and a quicker response is required [79]. The objective of CAPP is to take decisions on the following planning functions:

1- The manufacturing processes involved.

2- The machine tool set required to carry out these processes.

3- The cutting tools required for each stage of processing on each machine involved.

4- The fixtures required at each stage.

5- The sequence of operations required to produce each feature.

6- Cutting parameters such as: the number and depth of passes in a machining operation, the feeds and speeds appropriate to each operation, the type of finishing process necessary to achieve the specified tolerances and surface finish, etc.

To achieve these tasks, a compact, and organised structure for logic and rules is required for a CAPP system. This structure should be flexible to enable updating and revising of the logic and rules. Several methods have been used to organise decision logic. These are:

a. **Decision Trees:** A decision tree is a graphical representation of the decision logic. It consists of a single root and several branches [13]. Each branch corresponds a specific condition. Branches are connected by means of nodes. A node indicates a decision point at which a choice is made as to which branch to follow if a condition is true. This method is simple and easy to implement as computer code. A decision tree structure and a decision tree for process selection are shown in **Figure 2.2 (A & B).**

b. **Decision Tables:** Algorithms for planning must be designed so that the system can be expanded easily. For the building of an expandable system the decision table technique is often used in preference to the decision tree [64]. The elements of a decision table are: (1) *Conditions*, (2) *Actions*, (3) *Rules*, and (4) *Action entry.*

Decision tables are designed to achieve two aims:

1- To identify all permitted actions.

2- To specify when an action should be performed.

An action takes place if the conditions are answered positively. Thus for every condition a corresponding actions can be found. The decision tree and decision table methods can both be easily implemented on the computer. However, they cannot cover all the process planning decision logic and

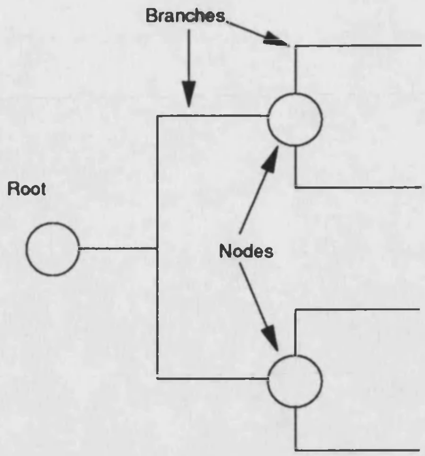


Fig 2.2-A: Roots, Nodes and Branches (after Chang and Wysk [13]).

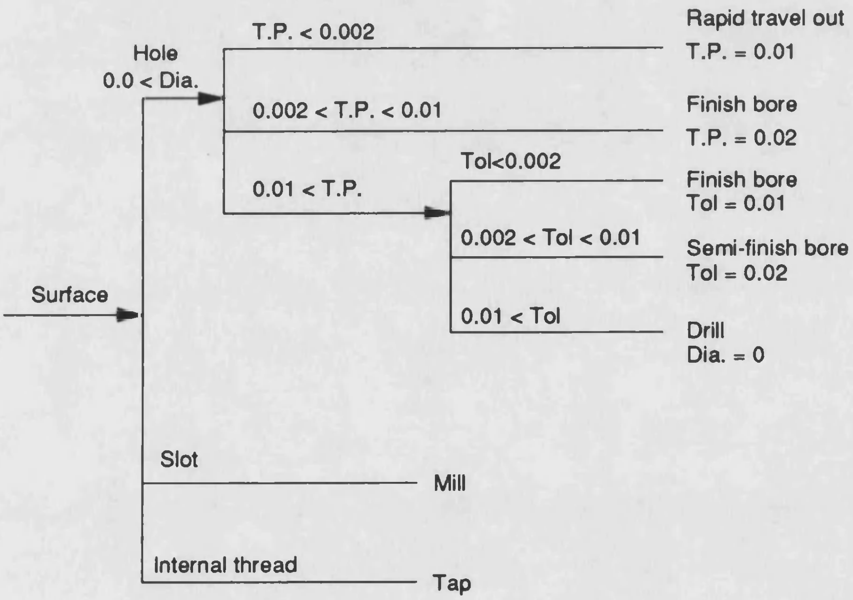


Fig 2.2-B: Decision tree for process selection (after Chang and Wysk [13]).

knowledge required; for example, they are not suitable for operation sequencing. The shortcoming of these methods has led to the development of Artificial Intelligence (AI) techniques. **Figure 2.3** shows the structure of the decision table.

c. **Artificial Intelligence:** Artificial Intelligence (AI) has become an important technique in manufacturing particularly in the process planning field. The structure of a knowledge based system or expert system resembles the intelligence of the human expert. The general principle is that the expert system uses a database and inference procedures to solve problems which normally require human expertise and knowledge.

Knowledge based systems offer a possible solution to process planning problems by inferring data from design models and analysing it with respect to advanced manufacturing technology methods [72]. Expert planning systems are now being widely developed in an attempt to solve the process selection and planning problems [23,45,51,56].

Knowledge based expert systems consists of two major components: (i) Knowledge Base, and (ii) Inference Engine.

i- Knowledge base: The knowledge base represents the expert knowledge. Expert knowledge includes; rules and factual knowledge. Factual knowledge consists of information about specific materials or technical parameters. Rules in the knowledge base can be expressed in the following form;

IF < Condition(s) > THEN < Action(s) >

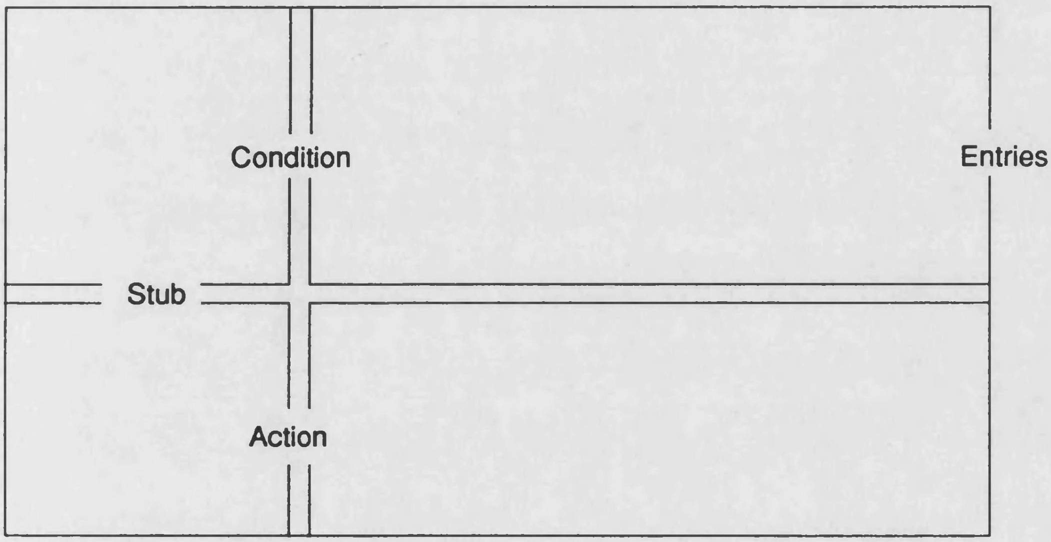


Fig 2.3 : Decision table partitions (after Chang and Wysk [13]).

To solve problems, the system searches for rules stored in the knowledge base with a high certainty factor, applies them and thus finds part of a solution space. A database link exists to enable large quantities of knowledge to be stored. The fundamentally different procedures within expert systems require the use of appropriate programming languages [69]. Several knowledge methods in expert system have been used in process planning [14,30,36] such as semantic nets, production systems, frames, logic, etc.

ii- Inference Engine: This is the control strategy for using the knowledge base to solve a problem. It contains the operating rules or the rules that apply the production rules to the factual knowledge to drive a set of assumptions through the system knowledge base to a conclusion. Control strategies in inference engines are of two main types [7]; (a): Forward chaining (FC), and (b): Backward chaining (BC). These two types can be explained as follows:

FC: Facts --> search for possible Rules to achieve --> Goal

BC: Goal --> search for possible Rules relative to --> Facts

In an expert system, forward chaining and backward chaining are often combined in different ways in order to achieve the main objective.

2.4.3 Databases

A database is a comprehensive collection of interrelated information stored on some kind of mass data storage device. Generally, it consists of information organised into a number of fixed-format records with logical links between associated records. Typically it includes operating system instructions, standard parts libraries, completed designs and documentation, source code, application programs, materials types and specification, as well as the user plans in progress. This database comprises all the information needed to manufacture components. It is designed in a way that facilitates easy updating of the files when any changes are made.

2.5 Generative Computer Aided Process Planning Systems for Prismatic Parts

A generative CAPP system synthesizes the design of the optimum process sequence, based on an analysis of part geometry, material and other factors which could influence manufacturing decisions. Several generative CAPP systems have been developed but typically these have been at the research level. The following sections review the most important of the existing generative CAPP systems that have been developed for prismatic components.

2.5.1 APPAS System

Automated Process Planning and Selection (APPAS) [82] is a generative CAPP system. It was written in the standard FORTRAN language and designed for milling and drilling machining processes. The COding FOR Machining (COFORM) coding system was used in APPAS to describe the surface of a part. The information required is feature based. The COFORM system describes each individual surface of a part using a data string of 30 to 40 attributes. It uses a decision tree logic for the decision making required to produce a single machined surface.

APPAS generates the process plan by analysing the data values of each individual feature that is captured by COFORM. The selection criteria aer based on comparing individual feature descriptions with process capabilities, which are represented in process boundary tables. The system also involves the selection of cutting parameters such as: cutting speed, feed rate, tool diameter, tool length, number of milling cutter teeth, depth of cut, number of passes. Time and cost estimation is also included in APPAS.

As mentioned, APPAS can only deal with individual machined surfaces. In order to have a complete process plan, all machined surfaces must be compiled manually in a form suitable for total process planning. In addition to this problem, the coding system is also carried out manually, which can be time consuming.

2.5.2 GARI

GARI [21] is structured like an expert system. It consists of a specialised knowledge base and a more general purpose problem solver. It is written in the MACLISP language and operates on the HP-68 computer. Knowledge in GARI is contained in production rules. The left hand side of a rule is a set (conjunction and/or disjunction) of conditions about the component, the available machines, and/or a machining plan. Items on the right hand side provide advice. They are sets of facts representing technological or economic preferences. Each piece of advice is weighted according to the importance of its satisfaction.

Conditions ---> Rules ---> Piece of Advice

The component is described to GARI interactively as entities such as: holes, grooves, bores, faces, etc. Dimensions and tolerances are input as they are on the drawing.

GARI is reported to have more than fifty rules available in it's knowledge base, most of them providing several pieces of advice (at the time of publishing the research, 1981). A large number of rules usually result in more conflicts among pieces of advice. The process planning sheet in GARI does not appear to contain full details of the plans, only the process selection and process sequencing.

2.5.3 CUTTECH System

CUTTECH [35] has been designed for machining operation planning. It is reported to consists of the following:

- An information gathering module.
- A knowledge base of machining rules.
- A controlling program.
- A database of machinability and tooling information.

The information-gathering module contains menu-driven decision trees to develop group technology codes to represent the component, material, machined features and machine tools required for the operation to be planned. The algorithms and decision tables for selecting the appropriate cutting tool, operation sequence, and the machining parameters are kept in the knowledge base. The controlling program manipulates the database which includes both machining parameter data such as: feed, speed, etc, and facility data which includes: machine tools, cutting tools, etc.

The modular construction in CUTTECH allows individual modules to be improved without affecting the performance of others. CUTTECH is claimed to be practical in nature and has an expert performance and is also claimed to have performed in a factory environment. However, it can only deal with each feature separately. CUTTECH also requires human interaction to make certain technical decisions that define the machining operations.

2.5.4 EXPLAN system

H. Muthsam and C. Mayer [57] described EXPLAN (the Expert System Application to Computer-Aided Generation of Process Plans and Support of NC Programming). The aim of this system is to remove the burden of routine tasks from the production planner through the use of an expert system. The main effort at the time of publishing the research (1990) was on planning milling with its complex sequence of operations.

The process planning model in EXPLAN is divided into three: workpiece geometry, machining, and planning. The geometrical data is used by the process planner as the basis for both the initial interpretation of the component and for several other activities in the course of planning.

> In the ***workpiece model***, prismatic parts are presented in machining-oriented mode, not in the geometrically oriented form of the design. This is because the machining-oriented mode is thought to be familiar to the production planner. Therefore the component is divided into individual, coherent objects, or *processing elements*.
>
> The ***machining model*** comprises the various types of planning knowledge. The planning knowledge is concerned with the changes in the geometry and properties of the component which can be brought about through individual production processes. The operation-specific planning requires knowledge of machining operations which can then be carried out using appropriate settings.
>
> In the ***planning model***, the processing elements, and the elementary operations, are allocated clamping positions. The aim of planning is to

maximise the work content of the individual setting, therefore the numbers of machine changes, tool changes, and changes of clamping positions are minimised.

The structure of EXPLAN is composed of dialogue, inference components and a knowledge base. These are connected to a CAD system. The dialogue component represents the interface for the user and assists the user in form or structure recognition. The foundation for structure recognition is the 3-D CAD system used by the designer to prepare the design. EXPLAN uses IGES to transfer the drawing information into the IAOGraph (Interactive Object-oriented Graphics tool) format. The IAOGraph format recognises processing elements consisting of combinations of surfaces and edges as well as their orientations and transfers this information to the system for planning preparation.

In the planning preparation module the following functions take place:

1. Determination of reference planes.
2. Determination of imperative sequences between processing elements.
3. Selection of groups of processing elements.
4. Selection of spindle positions of processing elements.
5. Determination of possible clamping positions for processing elements.
6. The checking of clamping characteristics of workpieces.
7. The splitting of processing elements into elementary operations.

The process planning of geometrically complex workpieces cannot be achieved on an economical basis unless the workpiece geometry is known to the system in a form which is relevant to process planning.

2.5.5 EXCAP system

EXCAP (Expert Computer Aided Process Planning System) was developed at UMIST by B.J. Davies and co-workers [17,18,77,83]. It has been aimed at providing all the data that defines a $2\frac{1}{2}D$ prismatic component, based on its IGES file, such that human intervention is minimised. It is written in the PROLOG language and runs on SUN workstations.

The data input to EXCAP is an IGES-based wire frame 3-D model; and in addition the dimensions, tolerances, and manufacturing instructions given in the engineering drawing are inputted manually. A separate module writes the information derived into the appropriate ASCII files for processing. However no details are given as to how the system converts this information into a process plan.

2.5.6 Rotational Systems

As well as the CAPP systems developed for prismatic parts, several commercial and research CAPP systems have been developed for rotational type parts. Initially, these were based on the variant approach. But owing to the great and rapid changes in the field of design and manufacturing, researchers appear now to be concentrating on developing CAPP system using the expert system approach.

Some of the generative computer-aided process planning systems that have been published specifically for rotational component are; AUTAP-NC [28], ROUND [38,44], XCUT [9,39], EXCAP [19], Turbo-CAPP [78], and BEPPS-NC [84,85].

More information concerning computer-aided process planning systems can be obtained from the published book by Chang and Wysk [13], a paper by Eversham and Schulz [29]; and work prior to 1989 can be found in the book by Chang [12].

2.6 Critical Appraisal

From this review of the literature and a study of the relevant existing systems, the following observations can be made:

(1) The majority of the published CAPP systems have been aimed at rotational rather than prismatic components. That is because of the simpler 2-D problem involved.

(2) Virtually all of the CAPP systems for prismatic-type parts that have been reported, rely on a high level of interactive expert decision making at the input stage. The only exception to this are the *Variant* system types that have been typically developed for narrow ranges of components. However, variant systems are inflexible and cannot accommodate new component types without new additional logic in the form of family plans being created.

(3) No truly generative system exists for prismatic components (i.e. a system that can automatically generate plans for any component), but there is a perceived industrial need for such system.

(4) The traditional generative CAPP systems, which use decision trees and decision table methods to represent knowledge, cannot adapt effectively to a varying operating environment. However, an expert systems approach, based on a knowledge base, appears to overcome this problem and has the following advantages over traditional CAPP systems:

   a. The knowledge base can be easily updated and improved without affecting the entire system.

   b. It provides a good solution when more than one alternative is available.

   c. It is able to justify and explain any decision it has made.

(5) In process planning a large number of mathematical calculations are involved, and expert systems are not good at dealing with this type of knowledge. Therefore, a combinations of an expert system and a conventional algorithmic system is required in order to solve this shortcoming.

Chapter (3)

Information Philosophy of BEPPS-GSCAPPP

3.1 Introduction to BEPPS at Bath University

BEPPS [55] is a generative Computer-Aided Process Planning (CAPP) system under preparation at the University of Bath. It has been designed with a modular structure that includes modules for:

a. Conventional machines.
b. NC machines.
c. Tooling.
d. Fixtures.
e. Casting pattern and forging die design.
f. Cost estimating.
g. Links to both the CAD and production management systems.

The areas that are currently being developed to provide a complete process planning system are illustrated in **Figure 3.1.** BEPPS has three major process planning modules. Each module is constructed to run on its own. These are:

BEPPS-ROT

BEPPS-NC

BEPPS-GSCAPPP

All these three process planning modules use a similar general structure as shown in **Figure 3.2.** According to the component type and machining environment,

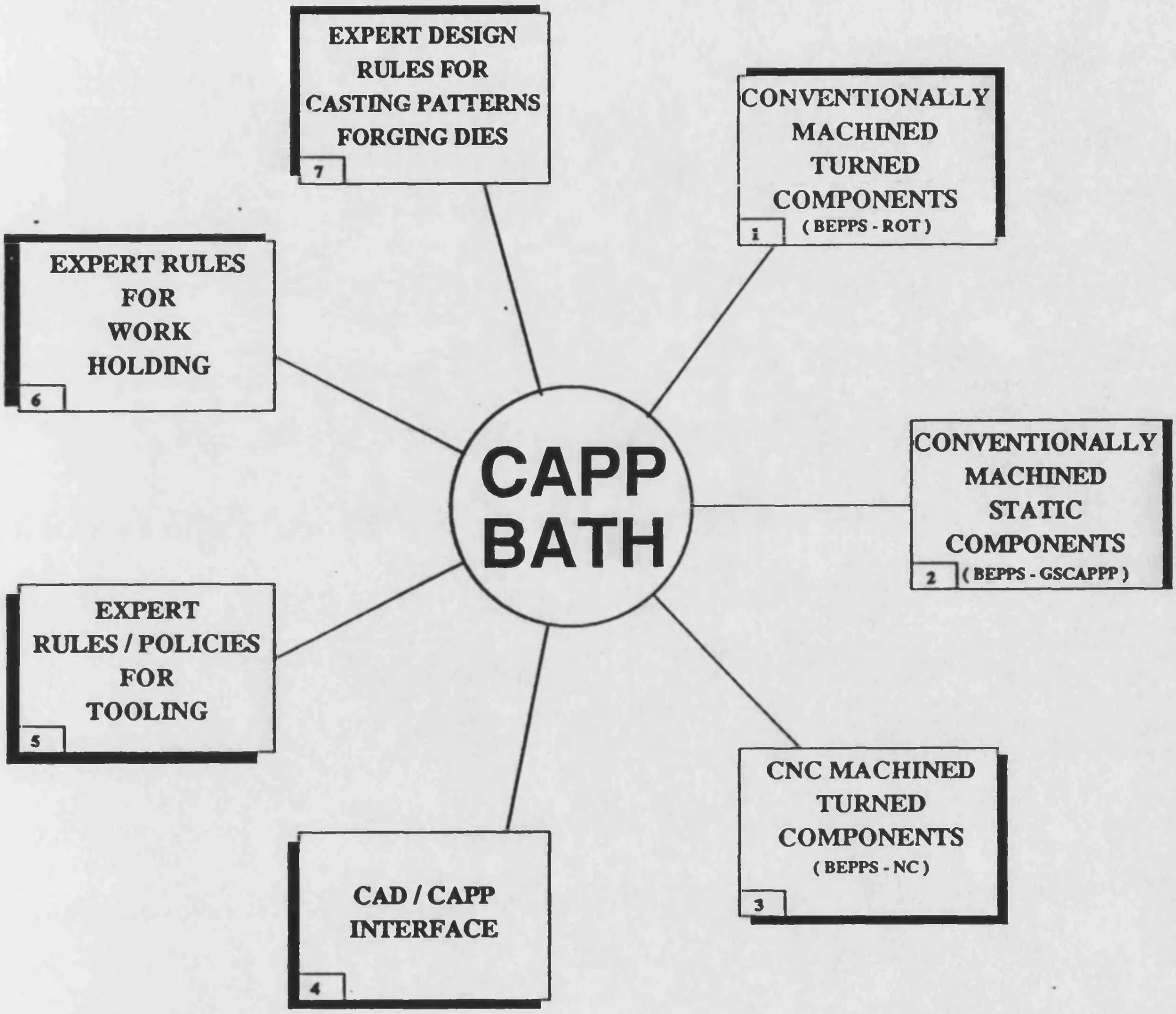


Figure 3.1: Overview of CAPP Research at Bath.

the planning is assigned to the appropriate module. Component information required to generate a process plan is put in each module either interactively through a dialogue or by a CAD interface. Basically, the component input information includes: material, basic size, features to be machined, and other general information.

The planning stage relies on expert production rules which have been elicited from industrial experts and other sources. These rules enable features to be ordered for manufacture and the appropriate machining operations and their sequences to be selected. The machine tool set, cutting tools, and machining conditions which are required to produce the component are also selected together with appropriate work holding devices.

This work presents a proposed system BEPPS-GSCAPPP: a generative computer-aided process planning system. It has been designed to generate process plans automatically for prismatic components in a conventional machine tool environment. Details of the research system are provided in the following chapters.

3.2 BEPPS-ROT

BEPPS-ROT [40,41] is a feature-oriented generative computer-aided process planning system. It is designed for automatically planning rotational components produced in a conventional machine tool environment. It contains two main stages:

1. ***Interactive input stage***, which provides the system with the component code, features to be machined and general information. Features in BEPPS-ROT are limited to 14 feature types. A graphical display of the component is automatically produced from the input data.

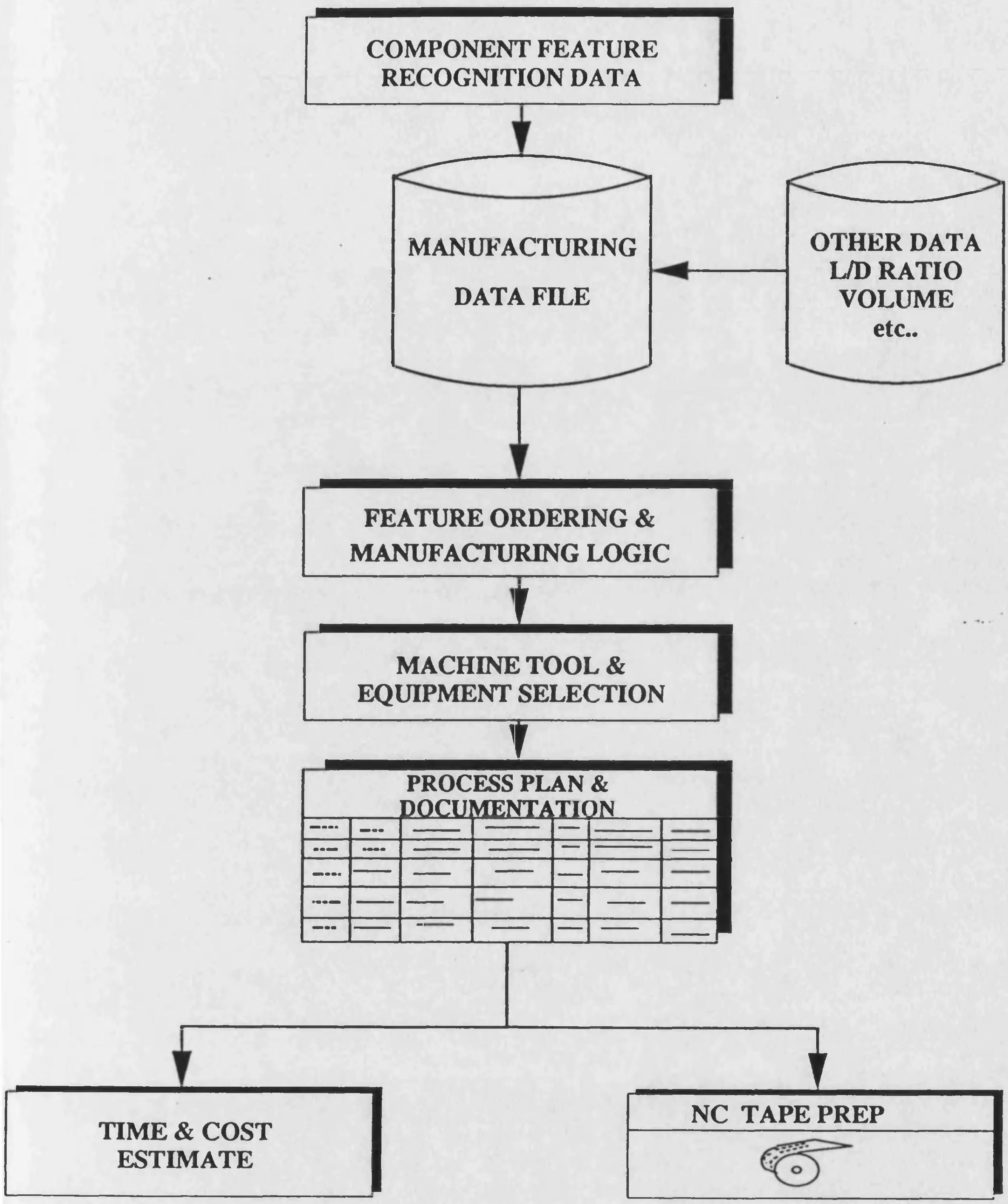


Figure 3.2: General BEPPS Structure.

2. *__Process planning stage,__* which generates a process plan for a given component automatically using expert rules and logic to select appropriate machining operations and their sequence, machine tool, cutting tools, cutting conditions, and workholding methods and gripping location, and finally produces a detailed process plan.

The system in its present state contains three rule-based modules: (1) Machine tool selection, (2) Non-machining operations selection (particularly the workholding methods), and (3) Feature ordering.

3.3 BEPPS-NC

BEPPS-NC [84,85] is a knowledge-based generative computer-aided process planning system. It has been designed to generate process plans for rotational components in an NC environment. The system is divided into two stages:

1. *__Input stage,__* where the component input information is put in either interactively by the planner or directly from CAD via a DXF data file. Seven feature types can be used to describe the component. Once the input data has been completed, a multiple graphic display of the component is then produced on the screen for verification purposes.

2. *__Process planning stage,__* in which the system uses knowledge-based rules and component data files to generate automatically a detailed process plan for a given component. It also generates automatically a NC part program, and is able to display a tool path view on the screen.

BEPPS-NC has in its knowledge base four modules: (1) Workholding selection, (2) Operation selection and sequencing, (3) Cutting tool selection, and (4) Machining data selection.

3.4 Knowledge Acquisitation and Representation

This section primarily deals with knowledge acquisition, and knowledge representation.

3.4.1 Knowledge Acquisition

Knowledge is defined in Collins dictionary as *the facts or experiences known by a person or group of people*. It includes heuristics, rules and expertise. Moreover, this knowledge is difficult to automate using traditional procedural and computer languages. Knowledge about a specific domain is acquired either from the study of published literature or from experts in the domain. Facts related to the domain are the components of the *declarative knowledge base* and rules or procedures which generate alternate paths of reasoning in the expert system are parts of the *procedural knowledge base* [49]. Typically knowledge can be classified into four categories [4]:

a. *Object knowledge*, the facts that describe the real situation relevant to the problem.

b. *Event knowledge*, the knowledge which indicates the time course of a sequence of effects and their cause and effect relationships.

c. *Performance knowledge*, the knowledge about application of skills or how to do things.

d. *Meta-knowledge*, deals with the extent, reliability and relative importance of specific facts, and how they evolved.

Knowledge is the most important element in process planning. It provides information for CAPP systems to enable planning activities to be performed. Manual systems rely on practical experience, catalogues, guides, etc. Therefore, a systematic data collection and interpreting module is required for CAPP systems to facilitate planning to be carried out [64]. In variant CAPP systems, information is contained within standard plans and only small amounts of basic information such as machining time need to be calculated [13]. However, a generative system makes all the decisions based on the knowledge stored in the system. Therefore, full information must be embedded and represented in such a way that can be easily implemented.

As discussed in [4,36], there are several methods to elicit the knowledge for process planning. These can be generally classified into three categorises:

1. Analysing text books or operator's manuals.
2. By interviews, group discussion, and questionnaires.
3. Observing people at work and analysing their behaviour, because often the operator is unable to give a verbal description of his skill, or suggest a correct basis for it [4].

The knowledge base system adopted by BEPPS-GSCAPPP includes two types of knowledges: (1) *Factual Knowledge*, and (2) *Procedural Knowledge*.

3.4.1.1 Factual Knowledge

Factual knowledge includes information about the facts that describe a factual function relevant to the problem. For example, to plan a component, specific information has to be available to generate a process plan for that component. Factual knowledge in BEPPS-GSCAPPP is divided into: a. *External Factual Knowledge* and b. *Internal Factual Knowledge.*

a. *External Factual Knowledge* deals with the extraction of information required for the planning of a component. This information includes specific details about the component's material, shape envelope etc. External factual knowledge is put in to the system via an interactive module which is discussed in Section 4.3.

b. *Internal Factual Knowledge* is that information which is stored in different modules in the system to perform certain activities. This kind of information is specifically selected and set for the system and includes such information as: the machine tool set and cutting tools, etc. It is built into the system in a flexible way in order to be updated easily. The internal factual knowledge has been elicited from various catalogues and archived [5].

3.4.1.2 Procedural Knowledge

Procedural knowledge contains the information needed to transform the blank into a finished product. It deals with the methods to be used to find relevant facts and to draw inferences. It comprises rules, how to use them and how to build control into the search strategy. Two main procedural knowledge bases are contained in BEPPS-GSCAPPP:

1. *General procedural knowledge* consists of general knowledge about processes. General knowledge refers to the relevant material presented in handbooks, textbooks and published research. It actually represents the methods rather than the rules of operation processes.

2. *Procedural rules* are constructed to achieve an effective process route. They are formulated to select the most appropriate machine tool set, cutting tools, cutting conditions, machining operations and their sequence, etc. These rules have been obtained by consulting various experts in the field as well as handbooks, etc.

As stated procedural knowledge and rules, for BEPPS in general and particularly for BEPPS-GSCAPPP, have also been elicited from existing CAPP systems, published reference books and a variety of other sources as follows:

a. Visiting several manufacturing companies and discussing knowledge and rules with their process planners.
b. A range of specimen plans completed by production engineers from various companies.
c. Interviews and questionnaires.

A set of questionnaires were prepared and sent to a number of companies in the U.K. for eliciting particular knowledge for BEPPS. An example questionnaire on machining holes is given in **Figure 3.3**. Great effort has been made to develop a knowledge base system for BEPPS. For this research, special attention was paid to collecting knowledge for machining processes on conventional machines, particularly, for prismatic components.

3.4.2 Knowledge Representation

The representation of knowledge is best achieved using a combination of data structures and interpretive procedures [49]. Representation schemes in BEPPS-GSCAPPP have been worked out for components, machines, tooling, machining processes, etc. in order to provide the system with all the details necessary to derive a process plan. Information for process planning has been organised according to four schemes: (1) *Component description*, (2) *Machinability*, (3) *Technical information and rules*, and (4) *Optimum plan route*.

(1) *Component description scheme* represents prismatic component information which includes: component type (constant or non-constant cross-section), material (type and code), shape envelope (length, width and height), plane surfaces required for machining (surface code), features required on each plane surface (type, code, size, surface finish, tolerance, etc.). More details are given in Section 4.3.

(2) *Machinability scheme* this scheme defines the machining capabilities. To produce a specific feature, a number of parameters have to be taken into account. Such parameters as the machine tool set, cutting tools, fixture, etc. are looked at to see if they are able to produce this feature according to specification. For example, to produce a hole with a high accuracy, (a) a proper machine set has to be selected, (b) an appropriate cutting tool has to be

(1)

MANUFACTURING GROUP

SCHOOL OF ENGINEERING

UNIVERSITY OF BATH

QUESTIONNAIRE ON MACHINING HOLES

This questionnaire is about the machining of holes. The purpose of this questionnaire is to help research into Computer-Aided Process Planning (CAPP) which is being carried out at The University Of Bath.

We would be very gratefull if you would answer the following questions as accurately as possible. If you are unwilling to answer a particular question please cross it, and write letters NA for any question to which an answer is not applicable.

All information will be kept in strict confidence.

Many Thanks.

Q1. Do you use the following machines ? If so could you indicate the largest and the smallest hole size that you produce on it and the minimum tolerance that you could expect.
(Please use table -1- to answer this question)

MACHINE	Y\ N	MIN HOLE DIA (mm)	MAX HOLE DIA (mm)	MIN TOL. +\- (mm)
Radial drill	Y	ϕ4	ϕ50	±0.3
Piller drill	Y	ϕ3	ϕ50	±0.3
NC dill	Y	ϕ3	ϕ150	±0.012
Boring M\C (V or H)	Y	ϕ3	ϕ500	±0.003
Honing M\C	Y	ϕ130	ϕ130	±0.002
NC machining centre	Y	ϕ3	500	±0.005
Centre lathe	N	[illegible]	[illegible]	[illegible]
Capastan lathe	N	—	—	—
NC lathe	Y	ϕ18 MM	ϕ250 MM	±0.012
Internal grinding M\C	Y	ϕ20	ϕ130	±0.001
Others : specify VERTICAL LATHE	Y	ϕ20	ϕ800	±0.050

Table(1).

Figure 3.3: An Example Questionnaire on Machining Holes.

(Please ring Y or N in questions, 3,4,5,6,7 and 9).

Q2. What is the maximum size of component machined in your company ?
Length = 1800 mm, Width = 800 mm, Hight = 1500 mm,
Diameter = 500 mm.

Q3. Do you use the following raw materials ?
a. Cast Iron,(CI). Y N b. Carbon Steel,(CS). Y N
c. Aluminium Alloy,(AL). Y N d. Mild Steel,(MS). Y N
e. Brass Alloy,(BA). Y N f. Other (specify).

Q4. For conventional drilling using 2-flute twist drill :
A. Do you use any of the following features ?
1) Special point angles. Y N 2) Spiral points. Y N
3) Citroen point. Y N 4) Thick webbs. Y N
5) Others (specify).

B. What is the maximum length / diameter ratio used ?
The maximum length / diameter ratio is = 10 To 1 .

Q5. Do you use any other types of drills such as :
a. Spade drill. Y N b. Gun drill. Y N
c. 3-flutes drill. Y N d. Core drill. Y N
e. Sandvik D-bit drill. Y N f. Deep hole drill. Y N
g. Other (specify).

Q6. Do you always use a centre drill ? Y N

Q7. Do you use a pilot drill when manufacturing larger diameter holes?
Y N

Q8. What is the minimum and the maximum reamer size used ?
The minimum reamer size = 3.0 mm,
The maximum reamer size = 27 mm.

Q9. Do you consider that your company is mainly engaged in :
a. Batch manufacture. Y N
b. Continuous manufacture. Y N

Q10. What is the average component batch size that you deal with ?
The average component batch size = 25

Q11. How many modified or new process plans do you construct per year?
The modified process plans construct per year = 500
The new process plans construct per year = 1000

Figure 3.3: Continue.

Q12. Please fill table (2) giving the approperiate operations for each case, assuming that a through hole of specified diameter and tolerance is to be produced.
In detailing the processes, please consider that the raw material is either the most common materials used in your company or mild steel.
Please use the following codes to fill the table :

CD : Centre drilling. D1 : First drilling cut.
D2 : Second drilling cut. D3 : Third drilling cut.
BR : Boring. RM : Reaming.
HN : Honing. IG : Internal grinding.

The first row in the table shows an example to be followed.

Dia (mm)	Tol (mm)	Mat.	OP1	OP2	OP3	OP4	OP5
15	+\- 0.1	MS	CD	D1	RM	--	--
0.50	+\-0.050	MS	CD	D1	RM	—	—
0.50	+\-0.150	MS	CD	D1	—	—	—
1.00	+\-0.025	MS	CD	D1	RM	—	—
1.00	+\-0.010	MS	CD	D1	D2	RM	—
12.00	+\-0.005	CI	CD	D1	BR	IG	—
12.00	+\-0.025	CI	CD	D1	BR	—	—
12.00	+\-0.100	CI	CD	D1	BR	—	—
12.00	+\-0.250	CI	CD	D1	—	—	—
25.00	+\-0.010	CI	CD	D1	BR	IG	—
25.00	+\-0.030	CI	CD	D1	BR	—	—
25.00	+\-0.100	CI	CD	D1	D2	—	—
25.00	+\-0.250	CI	CD	D1	—	—	—
100.00	+\-0.040	CI	CD	D1	BR	—	—

Figure 3.3: Continue.

chosen, bearing in mind the hole size, tolerance and surface quality that are involved. Certain limitations and boundaries have been set for the system in order to achieve complete automation for process planning. Limitations are discussed in Chapter 1, and **Table 3.1** shows process boundaries for hole production.

(3) *Technical information and rules scheme* deals with a. *Production rules*, and b. *Technical information.* In order to formulate the information for the above mentioned schemes into a process plan, this information is subjected to the logic rules embedded in the system.

a. *Production rules* are designed to control the order of the machining processes. These rules suggest the operations, their sequence, the machine to be used for the operations, the cutting tools to be used, etc. Examples of two production rules are shown below.

(Operation Sequencing)
IF (FEATURE is HOLE)
AND (TOLERANCE is TIGHT)
{***operations suggested drilling reaming, boring, internal grinding***}.
THEN (drill-->ream.*OR*.drill-->bore.*OR*.drill-->bore-->grind)
{***choice depends on other parameters***}.

(Tool Selection)
IF (OPERATION is DRILLING)
AND (ratio of HOLE DEPTH to HOLE DIAMETER is greater THAN 3)
THEN (use DEEP HOLE DRILL)

Tool type / Boundary	Twist Drill	Step Drill	Core Drill	Deep Hole Drill	Reamer	Boring Bar
Smallest Tool Diam.	0.3	6.0	6.0	3.0	1.0	3.0
Largest Tool Diam.	75.0	50.0	32.0	50.0	60.0	150.0
Depth/Diam ratio	12	12	12	12	6	10
Surface finished (μm) (CLA)	1.6	1.6	1.6	1.6	0.8	0.4

All dimensions (except surface finish) in (mm).

Table 3.1: Process Boundaries for Hole Production.

b. ***Technical information*** is mainly concerned with the cutting conditions such as feed, speed, depth of cut, power, etc. Technical information is collected from different books, publications, catalogues and data supplied by different factories and machine/cutting tool manufacturers. Production rules and technical information work in parallel to ensure that each rule satisfies the information available. Further details and examples are discussed in Chapters 4 and 5.

(4) ***Optimum plan rout scheme*** usually more than one process plan route can be generated. This scheme is designed to select the optimum process route taking in account several parameters. *Cost* is the most important element in this scheme where machining and non-machining time are considered. All of these considerations and parameters are discussed in Chapter 5.

Chapter (4)

General Structure of BEPPS-GSCAPPP

4.1 Introduction

BEPPS-GSCAPPP generates a detailed plan for a given component that contains all information required by the workshop. It is written in the FORTRAN 77 language, and contains material, technology and database files.

This chapter concentrates on the basic structure of BEPPS-GSCAPPP, particularly, the interactive (input) stage, the automatic modules and the databases that have been completed.

4.2 BEPPS-GSCAPPP Structure

Figure 4.1 illustrates the general structure of BEPPS-GSCAPPP. Basically, it contains four options [64]:

(1) User's help.

(2) Process planning.

(3) Decision logic modification.

(4) Database file modification.

The user's help option provides general guidance on how to use the system at the initial stage. In options (3) and (4), the user can have access to both decision logic files and database files to enable updating and/or modification whenever it is required. A specially formatted file is designed to compile the system files automatically whenever any modification take place.

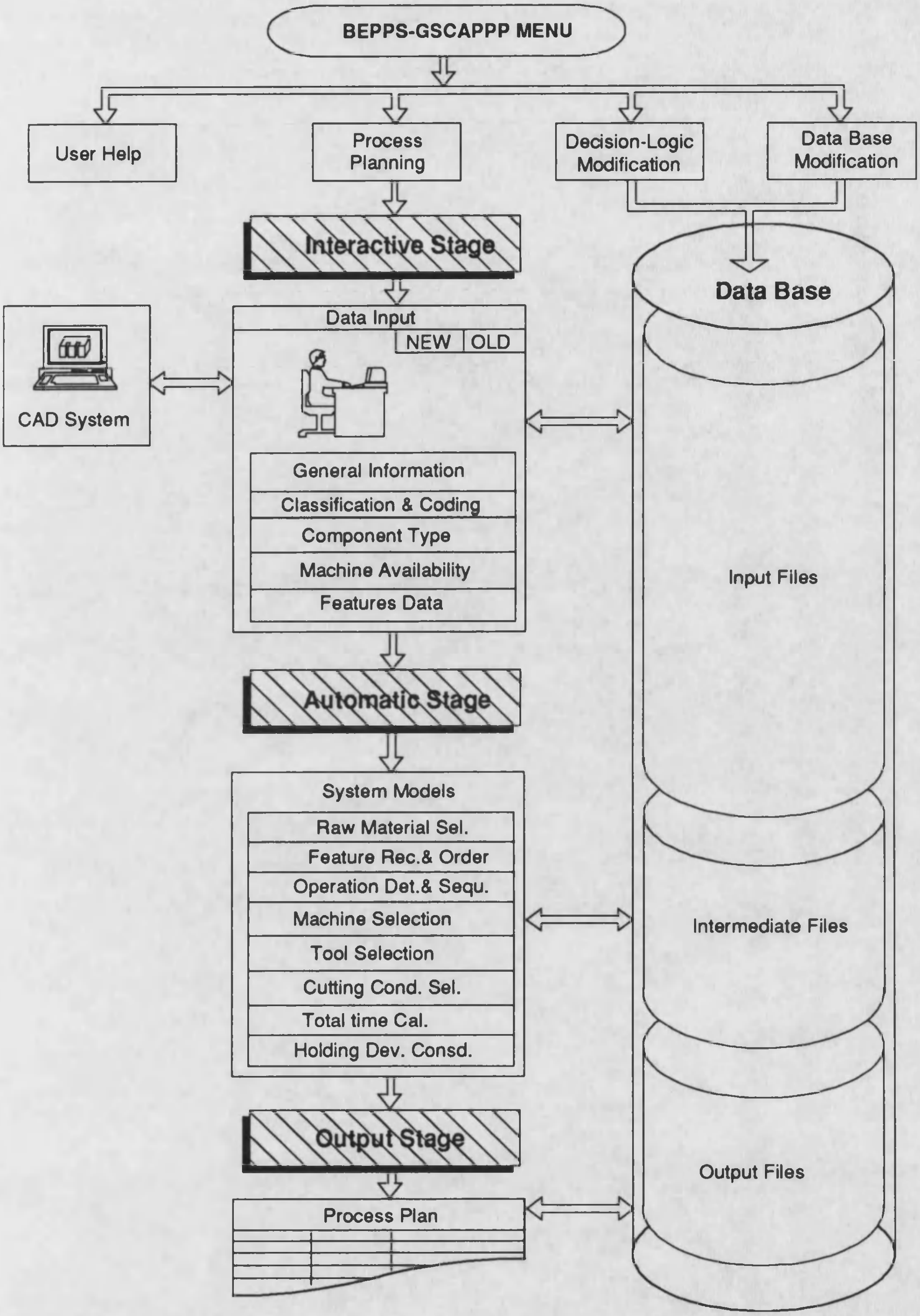


Figure 4.1 BEPPS-GSCAPPP General Structure

The main option is process planning which is divided into three stages: Interactive stage, Automatic stage, and Output stage.

4.3 Interactive (Input) Stage

In this stage, the planner provides the system with the input data required to generate the process plan. This stage is subdivided into the following sections: General Information Data Input, Component Classification and Coding, Component Type, Features and Machine Availability.

4.3.1 Section (1): General Information Data Input

In this section the planner is asked to input general information about the component, the production requirement, etc. (see **Figure 4.2**). The system requests the following information:

1. Component information:
   a. Name.
   b. Number.
   c. Material.
   d. Shape envelope (length, width and depth).
2. Production information:
   a. Batch type (discrete/continuous).
   b. Batch size.
3. Planner's name.
4. Date.

Once this information is completed, a header file for the procedure sheet is automatically saved.

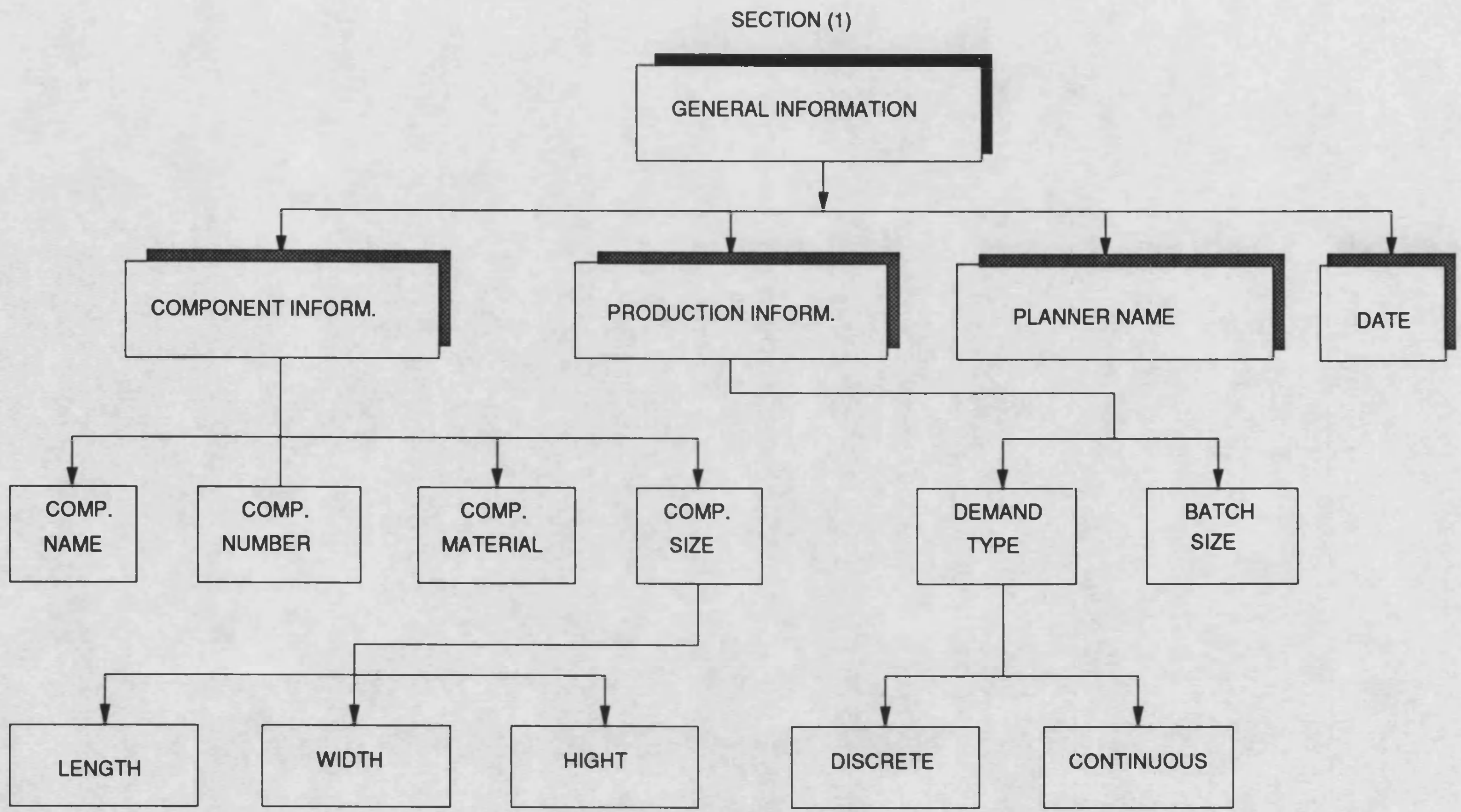


Figure 4.2 General Information Elements

4.3.2 Section (2): Component Classification and Coding

For development purposes the system considers only standard raw material forms. Of the variety of standard forms and sizes available, plate, flat, and square bar forms in selective sizes only are included.

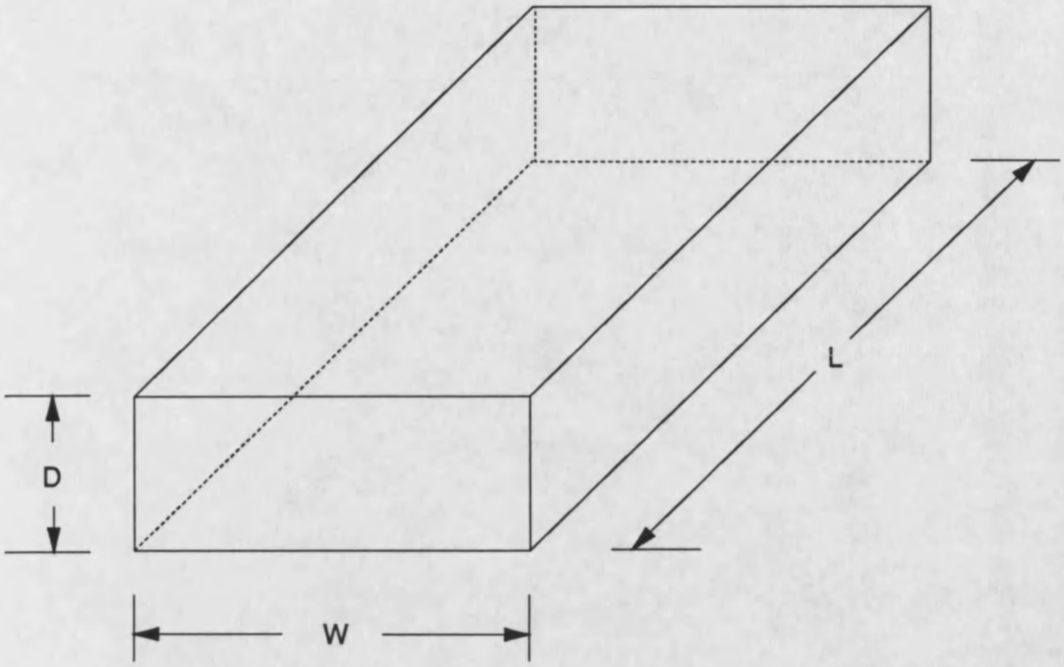
4.3.2.1 Component Class

A simple coding system has been designed to classify the component with reference to it's size (length, width, and depth). After the general information has been inputted, the system automatically classes the component into one of three types and displays the class type for verification by the planner. These classes [57] (as shown in **Figure 4.3**) are:

1. ***Flat component:*** A component is considered as flat if the ratio of its length to its width is less than or equal to 3, and the ratio of its length to its depth is greater than or equal to 4.
2. ***Long component:*** If the ratio of the length to the width is greater than 3, then the component is classified as long.
3. ***Cubic component:*** A component is classified as cubic if the ratio of the length to the width is less than or equal to 3, and the ratio of the length to the depth is less than 4.

This classification is carried out automatically and is used in the subsequent decision making processes.

It is necessary for the planner to be familiar with the system devised for coding both the planes and edges that form the shape envelope in which the component lies.



1. $\frac{L}{W} \leq 3$ & $\frac{L}{D} \geq 4$.......Flat component.
2. $\frac{L}{W} > 3$....................Long component.
3. $\frac{L}{W} \leq$ & $\frac{L}{D} < 4$..........Cubic component.

Figure 4.3 Component Class.

4.3.2.2 Plane Coding

As the system is designed for prismatic components, it is important to code the surface planes in a certain way, as this enables the planner to input the features in a distinct order for each plane.

Figure 4.4-A shows a 3-dimensional view of a block, and it's corner coordinates that consists of six surface planes. Generally, a plane is named with reference to the axis to which it is normal i.e. (x-plane, y-plane, or z-plane). The six surface planes of the component are divided into two types: ***Datum Planes***, and ***Opposite Planes***.

A ***Datum plane*** is a plane in which one corner is set at (x=0, y=0, and z=0). An ***Opposite plane*** is a plane which is parallel to the datum plane at an x, y, or z position appropriate to a specific component. It is clear that a component envelope has 3-datum planes and 3-opposite planes as shown in **Figure 4.4-B**. They are coded as follows:

Plane Surface	Plane Axis	Plane Code
	X-axis	XD
Datum	Y-axis	YD
	Z-axis	ZD
	X-axis	XO
Opposite	Y-axis	YO
	Z-axis	ZO

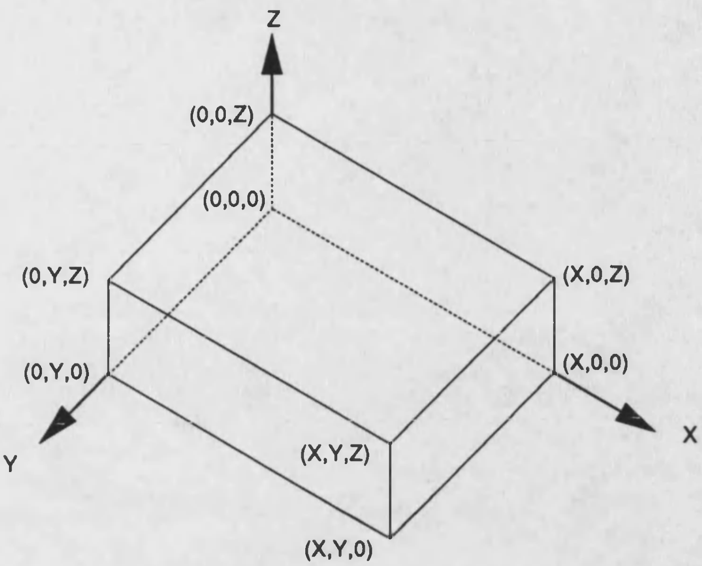


Figure 4.4-A: Corners Coordinates in the Component

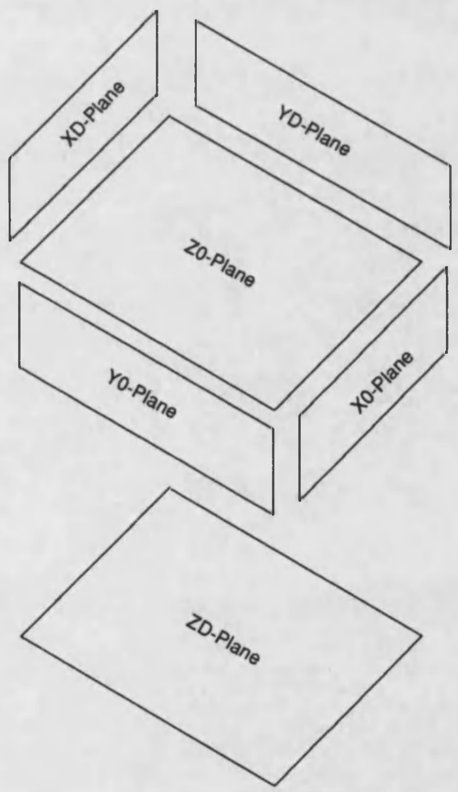


Figure 4.4-B: Datum & Opposite Plane of a Component

Initially, the planner has to conceive any component as a block and then assign the codes for the plane surfaces according to **Figure 4.4-B** taking in account the following restrictions:

1. The longest dimension must lie on the x-axis, and the shortest dimension must lie on the z-axis.
2. If any two dimensions are equal, then they should lie on x-axis and y-axis if they are longer than the third, or otherwise, on the y-axis and z-axis.
3. If all dimensions are equal, then there is no restriction.

The planner has to be familiar with the plane codes and to input them whenever they are requested.

4.3.2.3 Edge Coding

The edge code is used to recognize the position of a feature and for determining the machining direction. Edges in BEPPS-GSCAPPP are coded according to their plane positions. For example, the edges of the x-axis, are named as x-edges and coded as EX0 for the original x-axis, then moving in an anti-clockwise direction for the next edge EX1, etc. The same procedure is applied for original y-axis and z-axis. **Figure 4.5** illustrates the edge codes for the component envelope. For more details of the classification and coding system refer to Appendix A.

4.3.3 Section (3): Component Type

Furthermore, the entire component is classified according to its shape specification, i.e. the flat features required. This classification relys on:

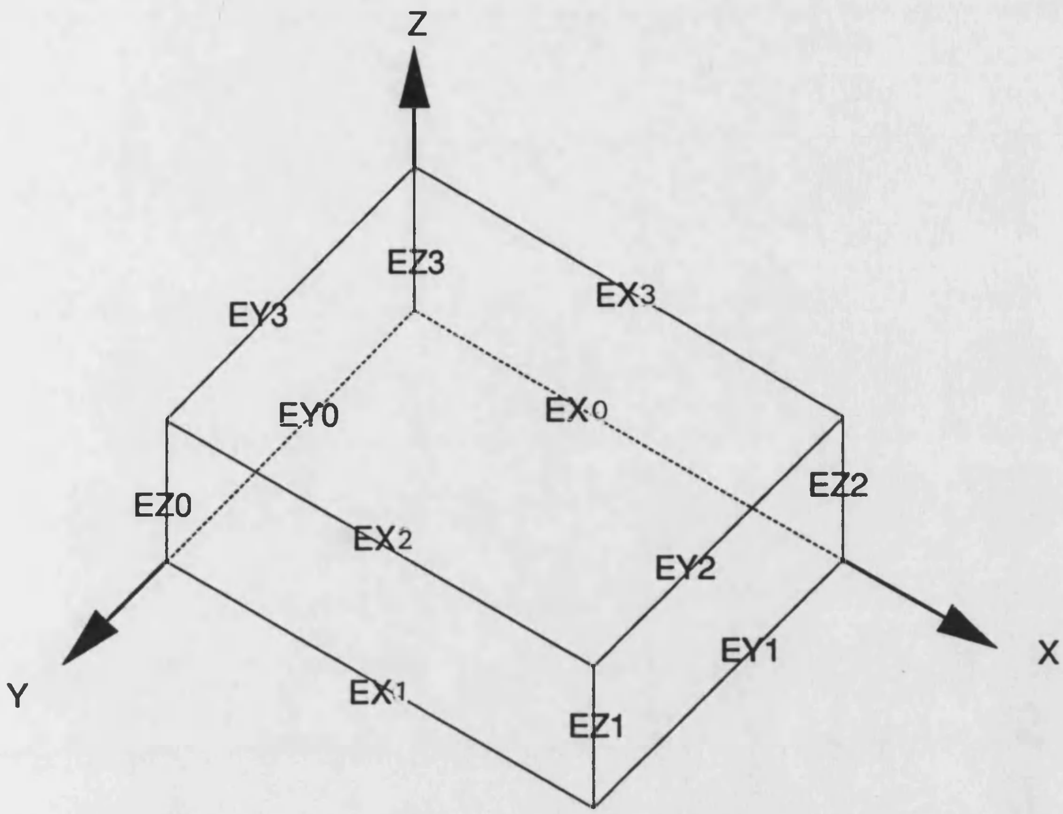


Figure 4.5 Edge Codes of a Component

a. The profile of the features across a plane surface.

b. The machining direction of features on a plane surface.

Prismatic components in BEPPS-GSCAPPP are considered as belonging to one of the following types:

(1) *Totally Constant Cross-Section Component:* A component is of Totally Constant Cross Section (TCX-SEC) if each of the surfaces that require machining have a constant profile in any plane direction. **Figures 4.6-A, B** and **C** show an example of a TCX-SEC component, a profile across the plane surface and the possible machining direction respectively.

(2) *Partially Constant Cross-Section Component:* A component is of Partially Constant Cross Section (PCX-SEC) if any one surface of those requiring machining has a constant profile in any one plane direction. Note that more than one surface must require machining. An example of a PCX-SEC component is shown in **Figure 4.7-A. Figures 4.7-B1** and **C1** show the profile of the non-constant plane surface and the machining direction and **Figures 4.7-B2** and **C2** show the profile of the constant plane surface and the machining direction.

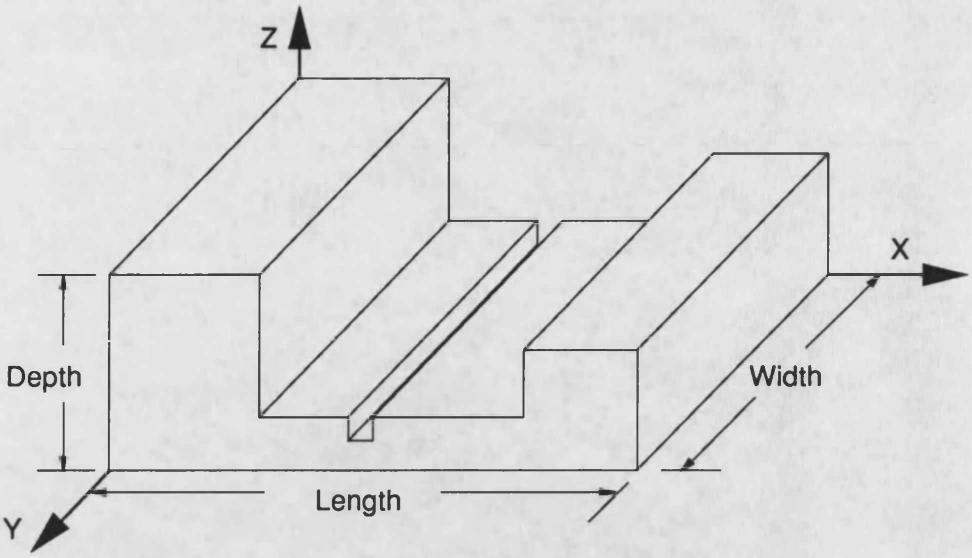


Fig. 4.6-A: Example of TCX-SEC component showing basic length, width and depth.

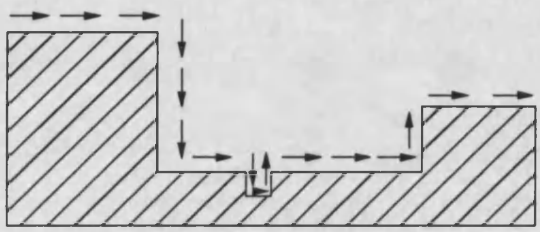


Fig. 4.6-B: Constant profile of ZO plane surface across the width.

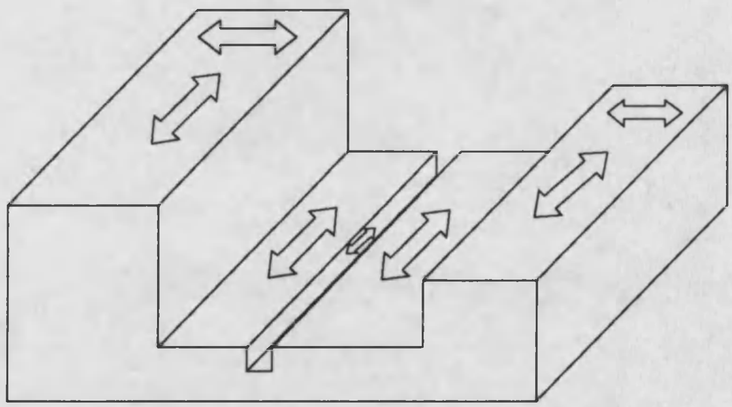


Fig. 4.6-C: Arrows shows machining direction either using vertical or horizontal milling machine.

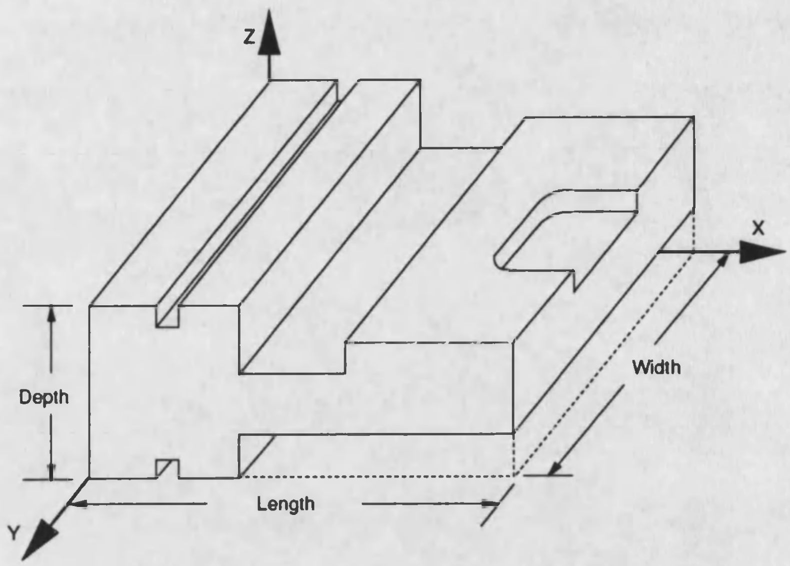


Fig. 4.7-A: Example of PCX-SEC component showing basic length, width and depth.

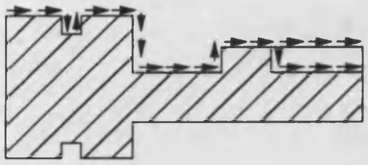


Fig. 4.7-B1: Non-Constant profile of ZO plane surface across the width.

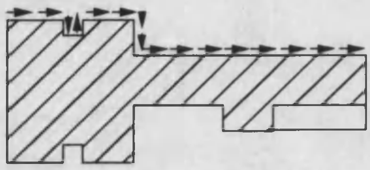


Fig. 4.7-B2: Constant profile of ZD plane surface across the width.

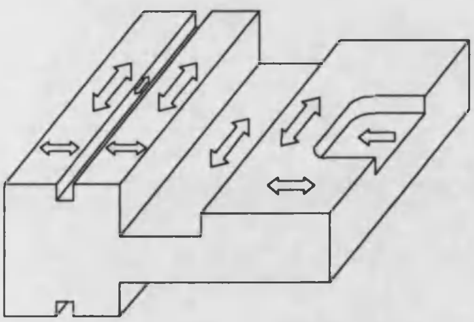


Fig. 4.7-C1: Arrows showing machining direction for ZO plane surface features.

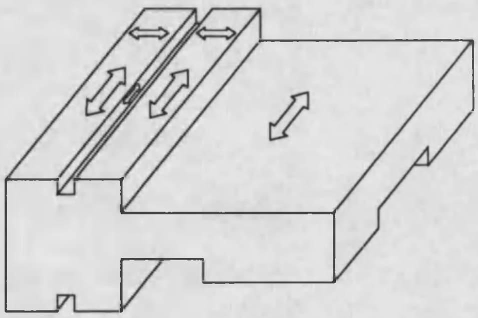


Fig. 4.7-C2: Arrows showing machining direction for ZD plane surface features.

(3) ***Non-Constant Cross-Section Component:*** A component is of Non-Constant Cross Section (NCX-SEC) if none of the surfaces requiring machining have constant profile in any one plane. An example of a NCX-SEC component is shown in **Figure 4.8-A. Figures 4.8-B1, B2, C1** and **C2** show the profile and machining direction of the two non-constant plane surfaces respectively.

A component is introduced to the system as either a constant or non-constant component. The component of partially cross section is initially considered as a non-constant component and therefore, once the planner has input the plane code, the system automatically asks about the type of plane surface being planned. The type of plane surface is classified according to each plane surface cross section in turn (constant or non-constant cross-section).

When identifying the component type, certain restricted conditions must also be satisfied:

a. Only cross-sections of plane surfaces requiring machining are considered.

b. The cross-section should be examined along the whole plane surface.

c. Cylindrical and other secondary features are not included when checking the uniformity of the plane surface profile.

At the input stage the planner is requested to identify the type of component being planned to assist the system to execute the process planning more efficiently. More information on component types are detailed in Appendix B.

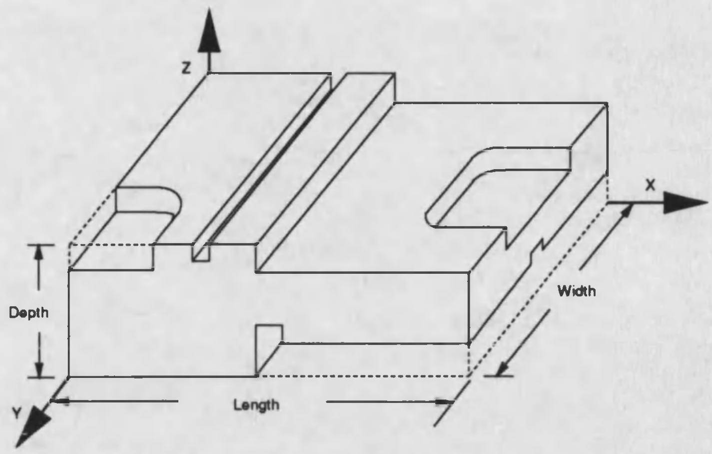


Fig. 4.8-A: Example of NCX-SEC component showing basic length, width and depth.

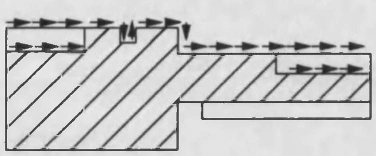


Fig. 4.8-B1: Non-Constant profile of ZO plane surface across width.

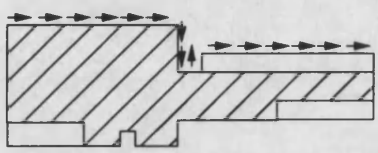


Fig. 4.8-B2: Non-Constant profile of ZD plane surface across width.

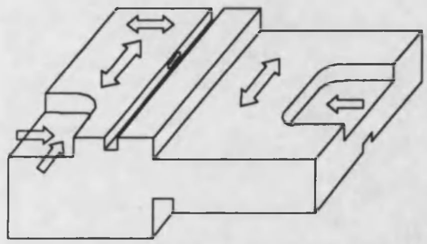


Fig. 4.8-C1: Arrows showing machining direction for ZD plane surface features.

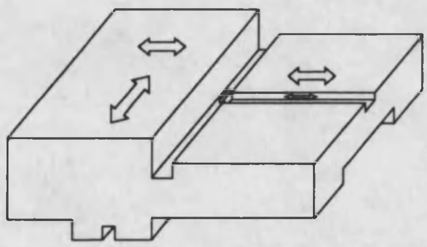


Fig. 4.8-C2: Arrows showing machining direction for ZD plane surface features.

4.3.4 Section (4): Features In BEPPS-GSCAPPP

BEPPS-GSCAPPP considers a range of the machined features that are commonly produced on conventional machines for prismatic parts. The simplified research version uses 7 features. These features are namely: flat surface, pocket, slots, plain hole, stepped hole, countersunk hole, and thread. As a further limitation only flat horizontal and vertical faces have been included. These features are divided into two main groups as described in the following section. **Figure 4.9** illustrates the system features.

4.3.4.1 Feature Classifications

The seven feature types have been classified into two major groups: ***Flat*** and ***Cylindrical*** according to the tool geometry and motion required to machine them.

1. The *flat group* includes faces, pockets, and slots.
2. The *cylindrical group* includes plain holes, stepped holes, countersunk holes and threads.

Each group is then subdivided into ***Basic*** and ***Secondary*** features as shown in **Figure 4.10.** The basic feature represents a primary form of the component and the secondary feature represent deviations from this primary form. This classification has been designed to give a much simpler feature ordering decision logic and to group features requiring the use of the same machine tool type.

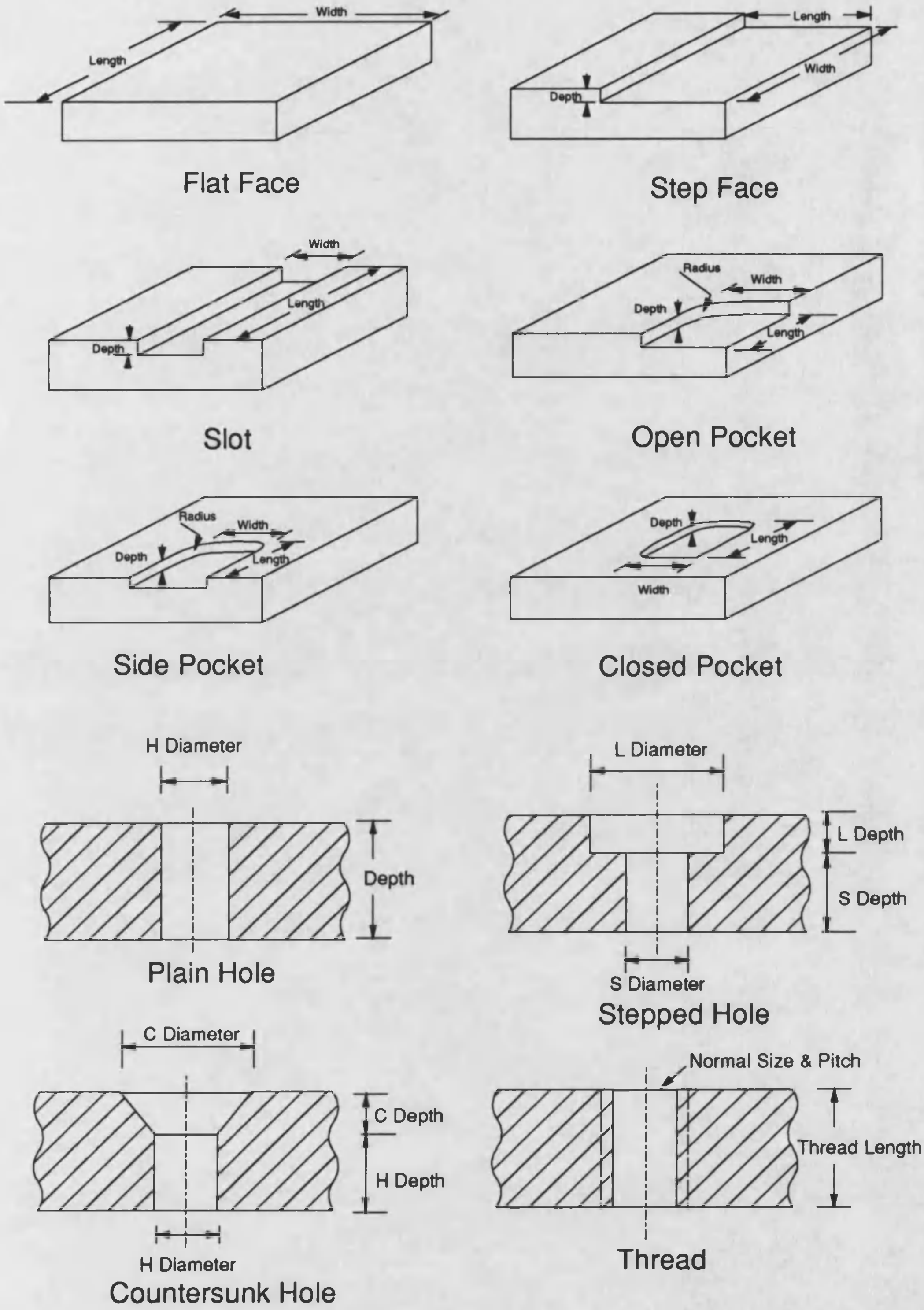


Fig. 4.9: BEPPS-GSCAPPP Features

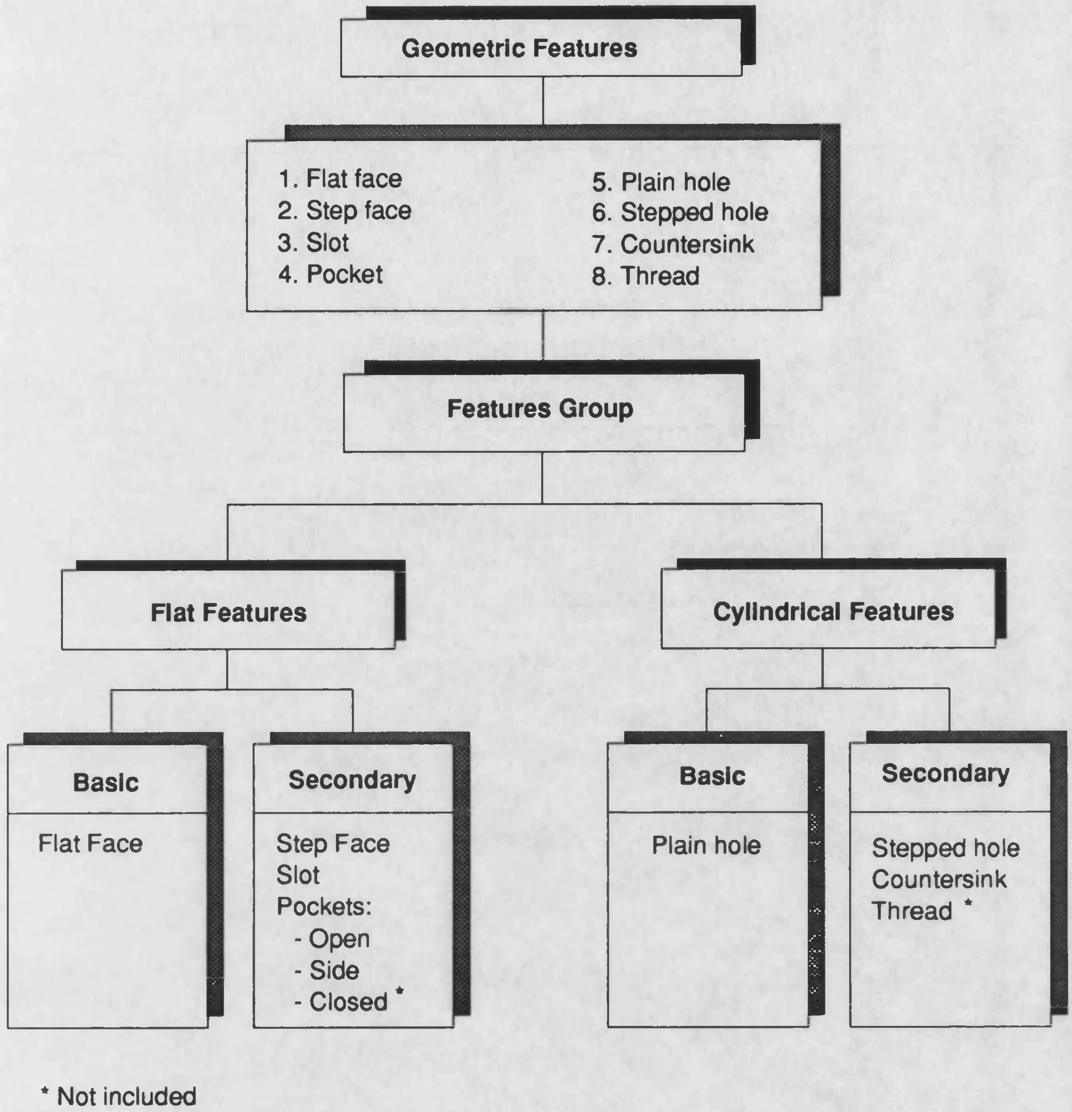


Figure 4.10 BEPPS-GSCAPP Featues Classification

4.3.4.2 Feature Data Input

The feature data for each plane surface that requires machining is put into the system inateractively via system prompts. Initially the planner is asked to choose one of the three main options after studying the component to be planned. These are:

a. Only flat features are required.

b. Only cylindrical features are required.

c. Both flat and cylindrical features are required.

Once the choice has been made the system then displays the range of features within the group for the planner to choose the appropriate feature set. In the case of choice option (c), information on the flat features is requested prior to that for cylindrical features.

For each feature, the planner is asked for a variety of parameters including: feature code, location, dimensions, tolerances, surface requirements, etc. These data are stored in a component database file that can be retrieved and processed by several modules. It has also been designed to accept feature information from CAD systems via a specially formatted file called **CAD-TRA** (*CAD-TRAnslator file*). Although the need for this file has been identified its design does not form part of this work. Feature parameters are elucidated in more detail in Chapter 5.

4.3.5 Section (5): Machine Availability

The machine tool database in BEPPS-GSCAPPP has been limited to contain the following machines:

(1) Vertical milling machine.

(2) Horizontal milling machine.

(3) Piller drill.

(4) Radial drill.

(5) Vertical boring machine.

(6) Surface grinder.

(7) Internal grinding machine.

Actual machine tools have been selected and these in turn impose size constraints on the components that can be machined by the system. **Figure 4.11** shows the general organisation of a theoretical BEPPS machine shop containing both these machines, turning and CNC machines. It also contains a sawing section and raw material and finished parts stores.

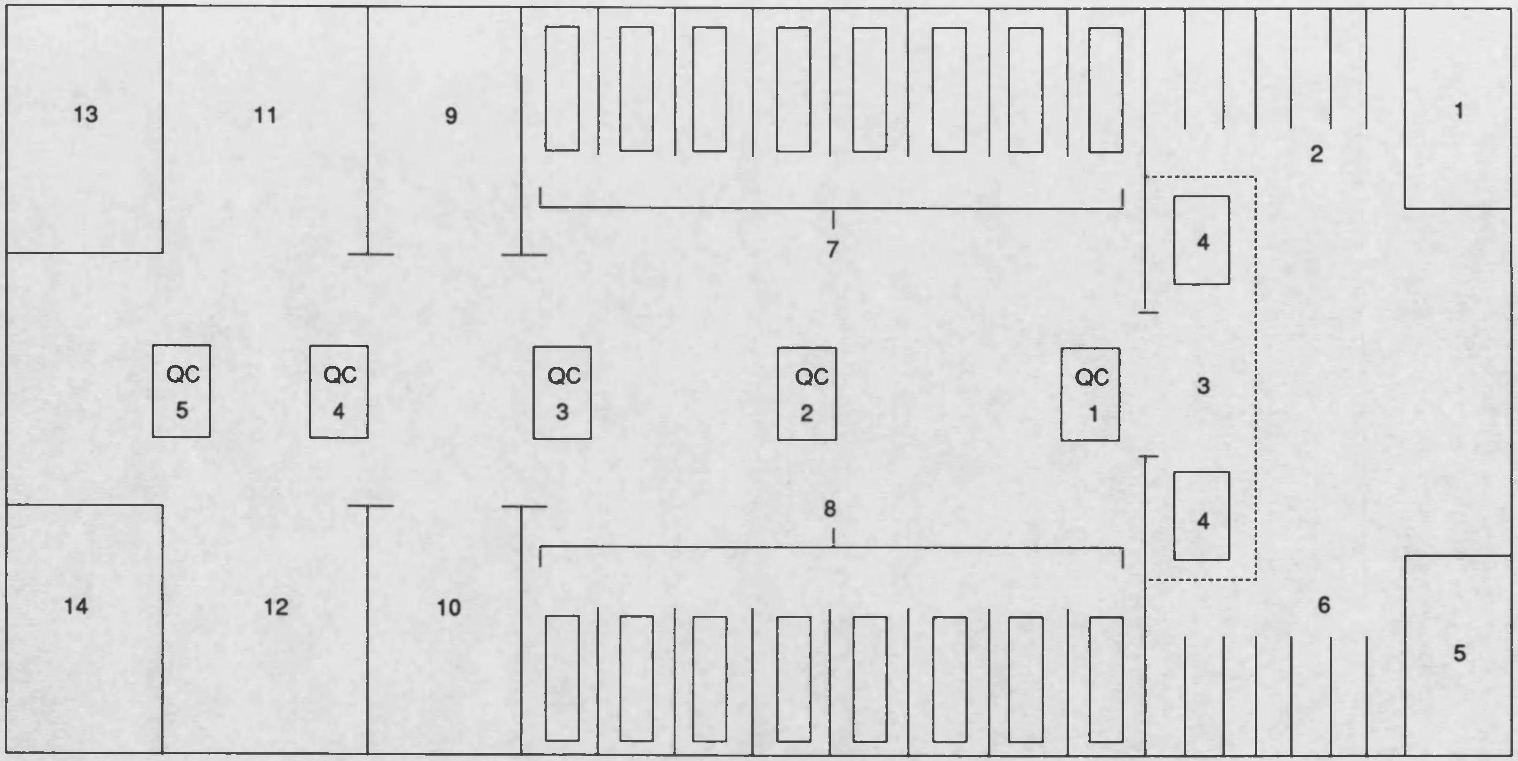
The system displays the machine tools (names and codes) so that the planner or production control system are able to delete machines that are currently occupied with other jobs.

4.4 Automatic Stage

Once the input of data has been completed, the system stores the information in a file named by the component number so that it can be either retrieved for modification or be used to generate a process plan automatically. The generation of a new process plan is constrained by any modification in the system or machine availability update. Process planning is divided into 8 modules as follows:

1- Raw material selection from stock.

2- Feature recognition and ordering.



1. Material Control Room
2. Round Bars Stock Store
3. Sawing to length Zone
4. Sawing Machine
5. Tool Room
6. Sheets, Plates, Flat, Square Bars Stock Store.
7. Turning Machines Section (Rotational Parts Machine).
8. Drilling, Milling, Boring, Grinding Machine (Prismatic Parts Machine).

9&10. NC Machines
11&12. Assembly Sections
13&14. Finished Parts Stores
QC. Quality Control Station

Figure 4.11 General Organisation of a Machine Shop for BEPPS

3- Operation determination and sequencing.

4- Machine tool selection.

5- Cutting tool selection.

6- Cutting conditions selection.

7- Total time calculation.

8- Workpiece holding device consideration.

All the automatic stage modules are discussed in details in Chapter 5. Database files which support these modules are discussed in Section 4.6.

4.5 Output Stage

When the process plan has been completed in full, it is printed in the form of a planning sheet (procedure sheet) that contains the following elements:

(1) **HEADER** which includes:

  i. General information.

  ii. Component information.

  iii. Production information.

(2) **PROCESS PLAN** which is divided into three sections according to the component design and machinability. These are: *CUT-TO-LENGTH* **(CUT-TO-LEN)**, *ROUGH-AND-FINISH FLAT* **(RUF-AND-FF)**, and *ROUGH-AND-FINISH CYLINDRICAL* **(RUF-AND-FC)**.

In the *CUT-TO-LENGTH* section the system displays the cutting plan for the provision of the component's raw material where an appropriate size is selected from stock. The plan details the cutting operation, material type and code, machine's name and code, the cutting length and the operation time.

In the *ROUGH-AND-FINISH FLAT* and *ROUGH-AND-FINISH CYLINDRICAL* sections the system outputs the process plan for flat and cylindrical features respectively in two separate forms. Each form includes:

- **i.** Rough and finish operations chosen and their sequences.
- **ii.** Machine tool set selected.
- **iii.** Cutting tool selected.
- **iv.** Cutting conditions selected.
- **v.** Total time calculated.
- **vi.** An indication of the type of workpiece holding device required.

The full structure of the output sheet is illustrated in **Figure 4.12**. Detailed process plan examples are shown in Chapter 6.

4.6 BEPPS-GSCAPPP Database Management

The database system provides the information needed for process plan generation. It facilitates data, representing the production tools available at a plant such as the type of machining operation, material to be machined, machine tools, cutting tools, cutting conditions, etc. Therefore, CAPP systems require data files to be constructed such that they can be manipulated by the system programs to

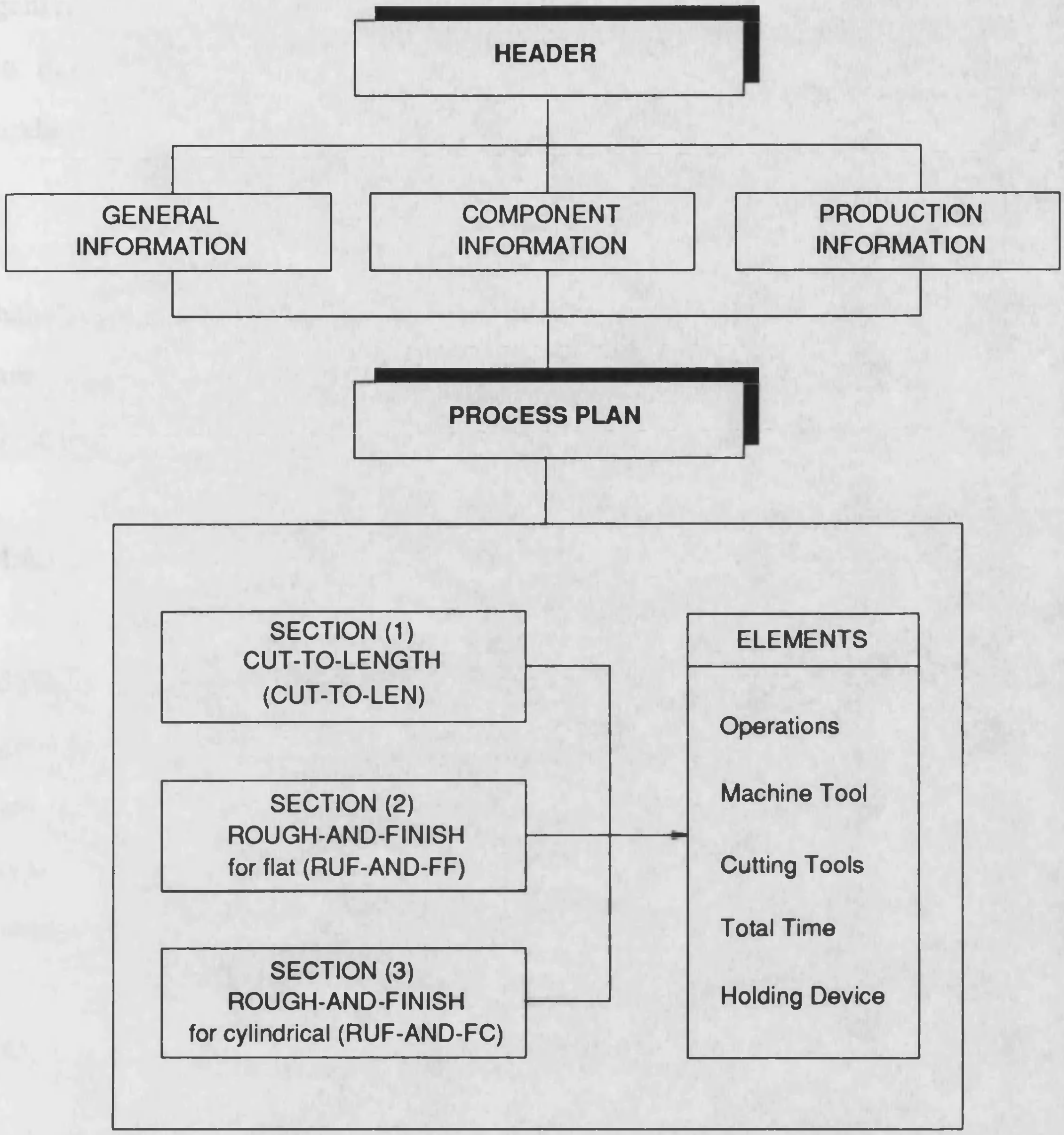


Figure 4.12 Structure of Output Sheet

generate machining operation plans. It is important during the design of the database to have regard for the flexibility of the system so that it can be accessed for updating and modification.

The database system in BEPPS-GSCAPPP is controlled by a novel database handling file that handles the three types of data stored in the system. The data types are *input*, *intermediate*, and *output* data. Each of these data are classified in the system as ***Temporary*** or/and ***Permanent*** data.

4.6.1 Input Data File

The input data file consists of component information which is stored in two different arrays: the part drawing and the technical information array, and the geometric definitions (features) array. These are generated in the main program and are passed to subroutines via an argument list. The input data is of a temporary data type. It could be stored as permanent data if it was indicated as such during the interactive stage, however, it can as temporary data still be modified and replanned.

4.6.2 Intermediate Data File

Intermediate data includes five control files which are permanently stored in the system to generate process plans. These files are: material control file, machine tool control file, cutting tool control file, cutting conditions control file and technology control file. Each file is constructed to control a number of files to facilitate updating, modifying files in it's group or transferring information from the subprograms to the technology file and thereof to the main program. For instance, the material control file is responsible for transferring data on the specified material, from the material stock file and material specification file to the technology file in order to select the appropriate material size and then to the main program. A complete set of intermediate data files are summarised in **Table 4.1**.

4.6.3 Output Data File

The output data file is an image of the process plan sheet. It stores the generated process plan initially as a temporary file; the planner then has to decide whether to keep it as a permanent file for future retrieval or not. If it is to be saved, the system automatically stores it using the component number as the file name. It is different to the input data file, in that the planner cannot add, delete or modify any of its data.

Control Files	Intermediate Files
Material Control file (MTCF)	Aluminium data file (ALDF) Mild steel data file (MSDF) Carbon steel data file (CSDF)
Machine Tool Control file (MCCF)	Surface Machine Tool file (SMTF) Cylindrical Machine Tool file (CMTF)
Cutting Tool Control file (CTCF)	Surface Cutting Tool file (SCTF) - Vertical miller cutting tool file (VMCTF) - Horizontal miller cutting tool file (HMCTF) Cylindrical Cutting Tool file (CCTF) - Drilling toole file (DTF) - Boring tool file (BTF) - Grinding tool file (GTF)
Technology Control file (TCCF)	Material Selection file (MSLF) Machine Tool Selection file (MTSF) Cutting Tool Selection file (CTSF) Cutting Condition Selection file (CCSF) Holding Device Consideration file (HDCF)

Table 4.1: Intermediate Data Files

Chapter (5)
Automation of BEPPS-GSCAPPP

5.1 Introduction

As discussed earlier, generative computer aided process planning systems are typically concerned with two main modules: (i) Identification of component features and their parameters and (ii) Automatic generation of a detailed process planning sheet including machining processes together with their cutting conditions. It is also necessary for automated process planning systems to integrate both machining and non-machining operations in one machining set up.

This chapter discusses the eight rule-based modules of BEPPS-GSCAPPP used for the automatic generation of process plans, that are specified in Section 4.4. Each of these modules can access the component data input file which enables all the subsequent decisions to be made automatically by the system.

5.2 Automatic Selection of Raw Material from Stock Module

The raw material selection module is a sub-module of the process planning module and for research purposes it has been restricted in size. It has, for example, a limited range of raw material types: mild steel, carbon steel and aluminium [8,71]. However it is considered that this limited range covers the majority of prismatic components machined from stock. The system is based on a small batch working shop that only machines components from stock and only keeps a small range of standard shaped bars, etc. This information is contained within the raw material database of BEPPS-GSCAPPP.

5.2.1 Raw Material Database

The raw material database consists of three different material files. Each file contains the information and specification of one of the included material types. Each file contains the available stock dimensions and each stock size has been given a unique code that enables faster data manipulation. The code has a combined alpha-numeric form which indicates material type, shape classification and size. For example MF2.5X30 is a flat mild steel bar of 25.00 mm by 300.00 mm cross section. **Figure 5.1** illustrates the mild steel material file.

5.2.2 Raw Material Information Retrieval and Analysis

When during the input stage the shape envelope dimensions are requested, the planner is asked to input the largest dimension as the length and the smallest as the depth. If any two dimensions are the same then they are requested as length and width if they are larger than the third etc. However the system has sufficient logic to check these dimensions and reorder them if an input error has occurred. As stated the dimensions are then displayed in correct notation for the planner to make a visual check.

When the overall dimensions have been verified and the feature and plane information put in the system checks to establish what-if any-material allowances are required in order to achieve the tolerances and finishes specified. This is carried out as part of the process planning module and uses expert logic to make the required decision. The expert logic which checks the need for any allowance is expressed in the following rule:

```
***************************************************************************
*                                                                         *
*  M   M  II  L      DDDD    SSS   TTTTT      DDDD        A      TTTTT    *
*  MM MM  II  L      D   D  S        T        D   D      A A       T      *
*  M M M  II  L      D    D  SSS     T        D    D    AAAAA      T      *
*  M   M  II  L      D   D      S    T   . .  D   D    A     A     T      *
*  M   M  II  LLLLL  DDDD    SSS     T   . .  DDDD     A     A     T      *
*                                                                         *
*-------------------------------------------------------------------------*
*                        Mild steel material file                         *
*-------------------------------------------------------------------------*
*                                                                         *
*          No. of bars = 50.              Bar length = 7 meters.          *
*          Tolerance = (+/-)0.25.         Roughness = 4.0 um.             *
*          Bar cross section; X  = Large dimension.                       *
*                             Y  = Small dimension.                       *
*                             MF = Flat.                                  *
*                             MS = Square.                                *
***************************************************************************
```

X (mm)	Y (mm)	CODE
25.00	20.00	MF2.5X2
30.00	15.00	MF3X1.5
40.00	20.00	MF4X2
45.00	25.00	MF4.5X2.5
50.00	25.00	MF5X2.5
65.00	45.00	MF6.5X4.5
70.00	50.00	MF7X5
80.00	35.00	MF8X3.5
80.00	50.00	MF8X5
90.00	30.00	MF9X3
90.00	40.00	MF9X4
100.00	50.00	MF10X5
110.00	25.00	MF11X25
120.00	20.00	MF12X2
130.00	30.00	MF13X3
140.00	25.00	MF14X2.5
150.00	50.00	MF15X5
180.00	40.00	MF18X4
200.00	50.00	MF20X5
220.00	40.00	MF22X4
250.00	30.00	MF25X3
250.00	80.00	MF25X8
300.00	40.00	MF30X4
350.00	40.00	MF35X4
400.00	50.00	MF40X5
20.00	20.00	MS2X2
32.00	32.00	MS3.2X3.2
45.00	45.00	MS4.5X4.5
65.00	65.00	MS6.5X6.5
85.00	85.00	MS8.5X8.5
105.00	105.00	MS10.5X10.5
125.00	125.00	MS12.5X12.5
130.00	130.00	MS13X13
140.00	140.00	MS14X14
150.00	150.00	MS15X15

Figure 5.1: Mild Steel Material File.

Allowance Check Rule:

(Check tolerance, and roughness at x-datum plane and x-opposite plane)

```
IF(XDT.GE.0.25.AND.XDR.GE.12.AND.XOT.GE.0.25.AND.XOR.GE.12)
OL = L
ELSEIF(XDT.GE.0.25.AND.XDR.GE.12.AND.XOT.LT.0.25.OR.XOR.LT.12)
OL = L + 4
ELSEIF(XDT.LT.0.25.OR.XDR.LT.12.AND.XOT.GT.0.25.AND.XOR.GE.12)
OL = L + 4
ELSEIF(XDT.LT.0.25.OR.XDR.LT.12.AND.XOT.LT.0.25.OR.XOR.LT.12)
OL = L + 8
ENDIF
```

(The same statement is applied to the y and z axis)

This rule may be translated as follows: If the required tolerance on either the datum or opposite planes of the x-axis are greater than or equal to the *"as supplied"* tolerance on the standard material form in respect to size, roughness and flatness then, no allowance is required on the length. If any of the conditions mentioned above are not met, then a fixed allowance of 4.00 mm is added to the length for each surface that requires finishing. The same logic is also applied to both y and z axis to check the allowances required on width and depth.

By using this metal addition technique the system changes the shape envelope of the finished component into the minimum shape envelope of the required raw material and details which surfaces if any are sufficiently accurate to negate machining.

5.2.3 Selection of Appropriate Raw Material Form

As described, during the raw material analysis stage the shape envelope of the required raw material is determined. This forms the base information for selecting the most appropriate raw material form. The database of standard forms assumes at present that each bar etc. is substantially longer than any component that the system can accommodate, hence only the X and Y cross-section dimensions of the raw material are important. A *"best"* fit comparison is carried out in order to match a component's shape envelope with the material's X Y dimensions. Basically the component's Length/Width, Length/Depth and Width/Depth are compared against all X Y material dimensions of the stock held. If there is an exact match, the matching algorithm is stopped and the material stock designated as the *"Ideal Form"* i.e. no excess machining is required.

If no ideal is available, then the database is searched to find the nearest fits. These are displayed on the screen together with the most appropriate stock size. The most appropriate stock size is arrived at automatically by taking into account the following factors:

(1) The minimum volume of excess metal to be removed.

(2) The minimum contact area for machining.

(3) The method of removing the excess metal.

By using these three factors the choice of the most appropriate stock size is based on a combination of minimum volume and economics. If for some reason outside the normal logic a different stock size is required then the planner can override the system and specify the new material form for further processing. **Figure 5.2** shows the structure of the material selection module [66].

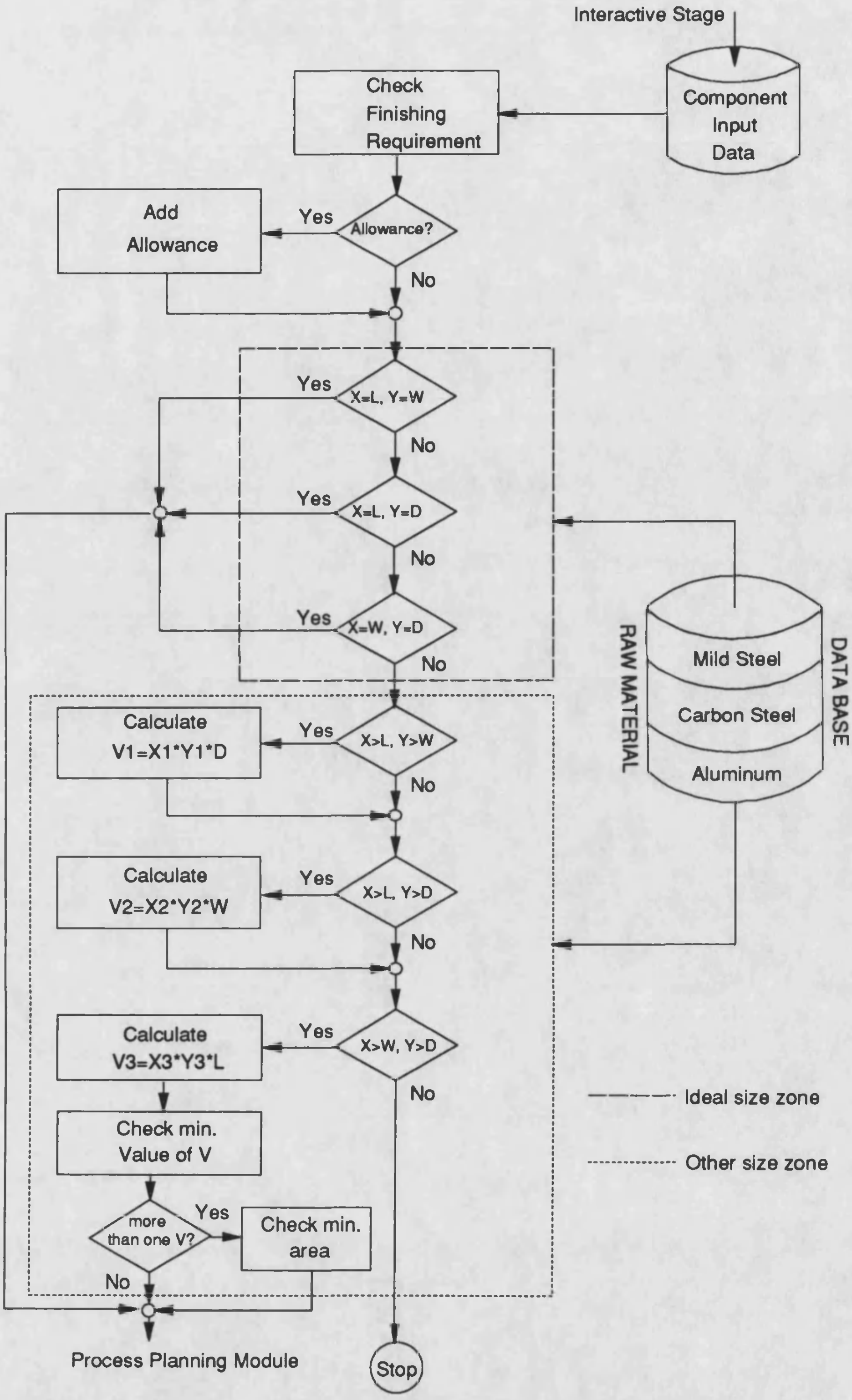


Figure 5.2: Structure of Raw Material Selection Module

5.2.4 Output of the Raw Material Module

Once the system has analysed the parameters and chosen the most appropriate form, the system displays the stock dimensions and code on screen for the planner to visually check; thereafter, the information is transferred to the Cut-To-Length **"CUT-TO-LEN"** module to select a cutting operation i.e. sawing or burning. The Cut-To-Length module is at present limited to sawing operations only. After this has been selected the information is put into the output file ready for printing onto the planning sheet which is printed when the process planning has been completed. It is also made available for use during feature ordering and operation selection etc.

5.3 Automatic Feature Recognition and Ordering Module

The main task of computer aided process planning systems is to determine the sequence of the individual processing operations needed to produce a finished component according to the design specification. Some partially-generative CAPP systems have concentrated, in general, on the automatic selection of the operations required to produce individual component features. However, the process plan for a component should not only include the sequence of operations for producing individual features, but should contain the order in which features are to be processed and whether features are to be processed individually or in combinations. Of the two, feature ordering is perhaps the most important element to automate and it has not, as yet, been satisfactorily included in any current CAPP system, particularly those for prismatic components.

In variant CAPP systems the feature ordering information is fixed within the *"Standard"* plans, whereas in generative systems expert precedence rules, based on the various constraints, must be formulated and embedded into the computer system. Today most of the existing CAPP systems for prismatic parts have either used rules that have been supplied interactively by the user [24] or automatically using very simple conditions [13]. PC-CAPP (S. Pande & M. Walvekar) [59] claims to generate plans for prismatic components but there is little indication of the level of interactivity required for feature ordering or the constraints placed upon the system in terms of component shape etc.

One of the main aims of BEPPS-GSCAPPP was to develop a system in which process plans were generated automatically. This module concentrates on the automation of the feature ordering process.

5.3.1 Feature Identification and Recognition

At this stage the system retrieves all information about the plane surfaces that require machining and asks the planner to input feature data for each plane surface individually, taking into account the following steps:

Step 1: Study the component design and then group the feature input data for each plane surface separately. The planner must neglect features on other planes which interact with a specified plane surface, i.e. features are dealt with once only and are included in their '*main*' plane.

Step 2: Identify the features on the plane concerned and the type of the plane surface profile. The profile of the plane surface can be classified as constant or non-constant cross section as mentioned in chapter (4). It is considered as constant if the plane is on a TCX-SEC component or its design meets the subsequent constraints on a NCX-SEC component:

a. Consists of a single flat feature type.

b. The profile of Flat features is uniform throughout the plane (having the same cutting direction). Otherwise, the plane is non-constant.

Step 3: Follow the feature input instructions to input the features as required either for a constant or non-constant plane type. For a constant plane surface the input sequence for the plane's features (especially the flat features) must be edited in the prescribed order using a *Top-To-Bottom* **"TOP-TO-BOT"** technique, whereas the *Scoring* **"SCORE"** technique has been designed for non-constant plane-surface feature input. Both techniques are discussed in the following section.

The feature data input module is designed to accept feature data for one plane at a time. The planner is required to input each feature presented in the form of a code. The computer system automatically recognizes the feature and displays a set of related questions. These questions elicit the feature parameters, such as: dimensions, tolerances, finishing requirement and location. This procedure is carried out for firstly the flat then secondly the cylindrical features on a designated plane, before moving to the next. Once feature data input for a plane is complete, the system saves the information in a file designated by the plane's code.

5.3.2 Feature Ordering Mechanism

As discussed above, there are two techniques used to input data efficiently. The *Top-To-Bottom* and the *Scoring* techniques [65,67].

The Top-To-Bottom technique is designed to input a feature's information with reference to its position on the plane. This means that the feature on the top level (greatest Z value for X plane, etc.) has priority over the bottom ones. An example of this technique is shown in **Figure 5.3**. This technique is applied only for flat feature types. If more than one feature exists on the same level, then the feature input sequence is left to the planner's judgement, or alternatively, the Scoring technique can be manually applied. The system accepts the input feature order for flat group features as the final order. This technique is manual, but it is effective for 3-dimentional (prismatic) components. The Top-To-Bottom technique is not concerned with the cylindrical feature order. The cylindrical features can be edited manually using the Soring technique.

In the scoring technique each feature (flat or cylindrical) is given a score based on its group. Each feature in the group is given a basic score. The basic score is appointed according to the appropriate machining order. The flat group for example typically has priority over the cylindrical group. This will result generally in plans showing *Mill* and then *Drill* i.e a hole will not be machined unless the face on which it is located has been completed. The scoring technique is used on the one hand to reorder features on a non-constant plane surface (flat features) and on the other hand to reorder cylindrical features based on the basic score. The principle of the scoring technique structure is to keep features in two separate files (flat and cylindrical) after giving each feature its basic score. **Figure 5.4** shows the hierarchy of the feature ordering using the scoring technique and the basic scores. This basic score is presented in a form of *'units'*.

The general structure of the feature ordering technique (SCORE) used is shown in **Figure 5.5**. This technique could be modified to perform the feature

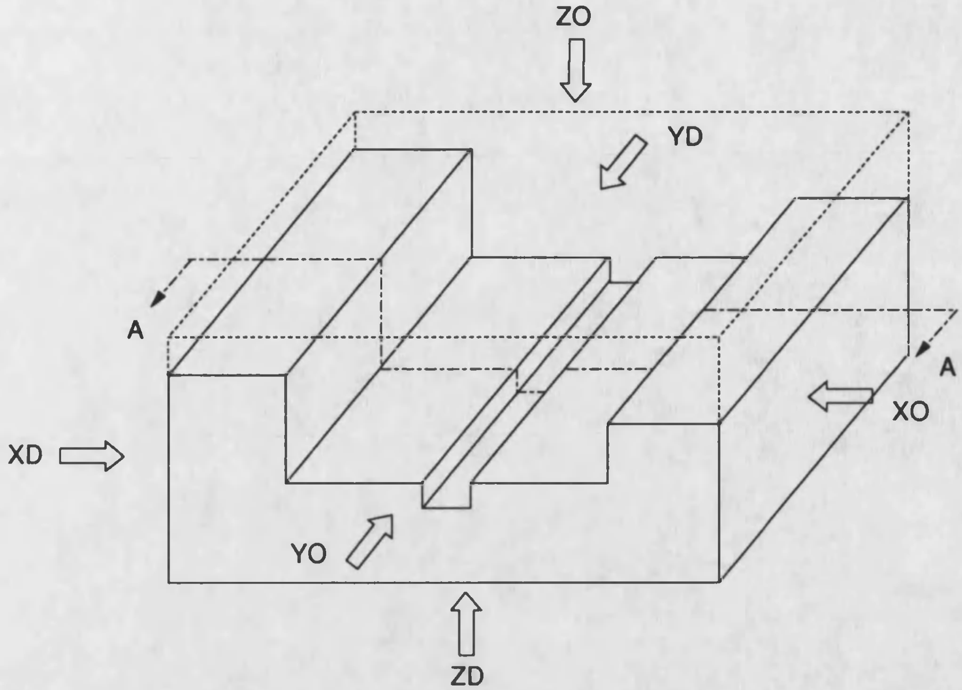


Figure 5.3-A: TCX-SEC component showing the six plane codes.

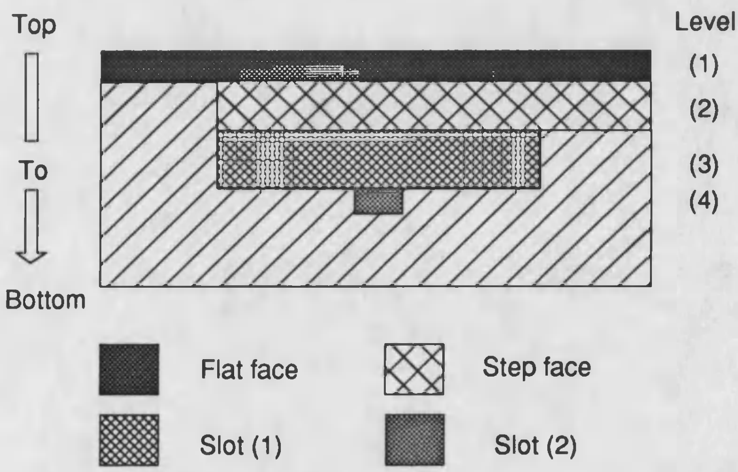


Figure 5.3-B: Top-To-Bottom technique presenting feature order on ZO plane surface.

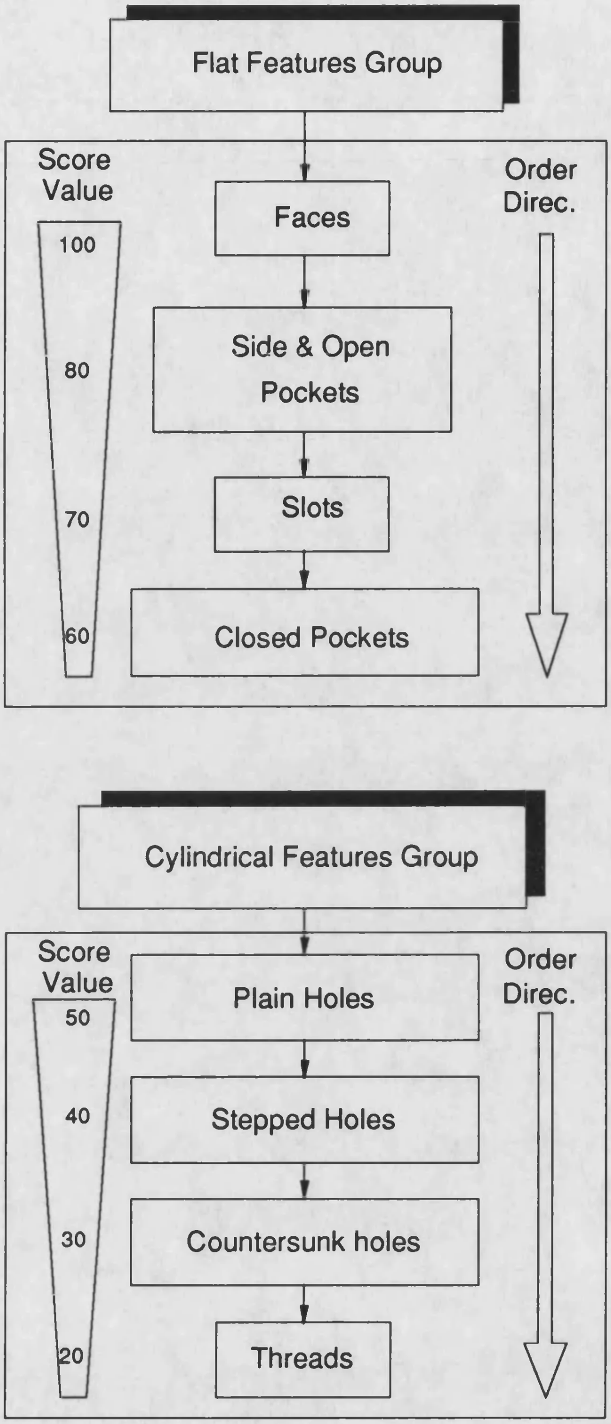


Figure 5.4: BEPPS-GSCAPPP Feature Ordering Hierachy.

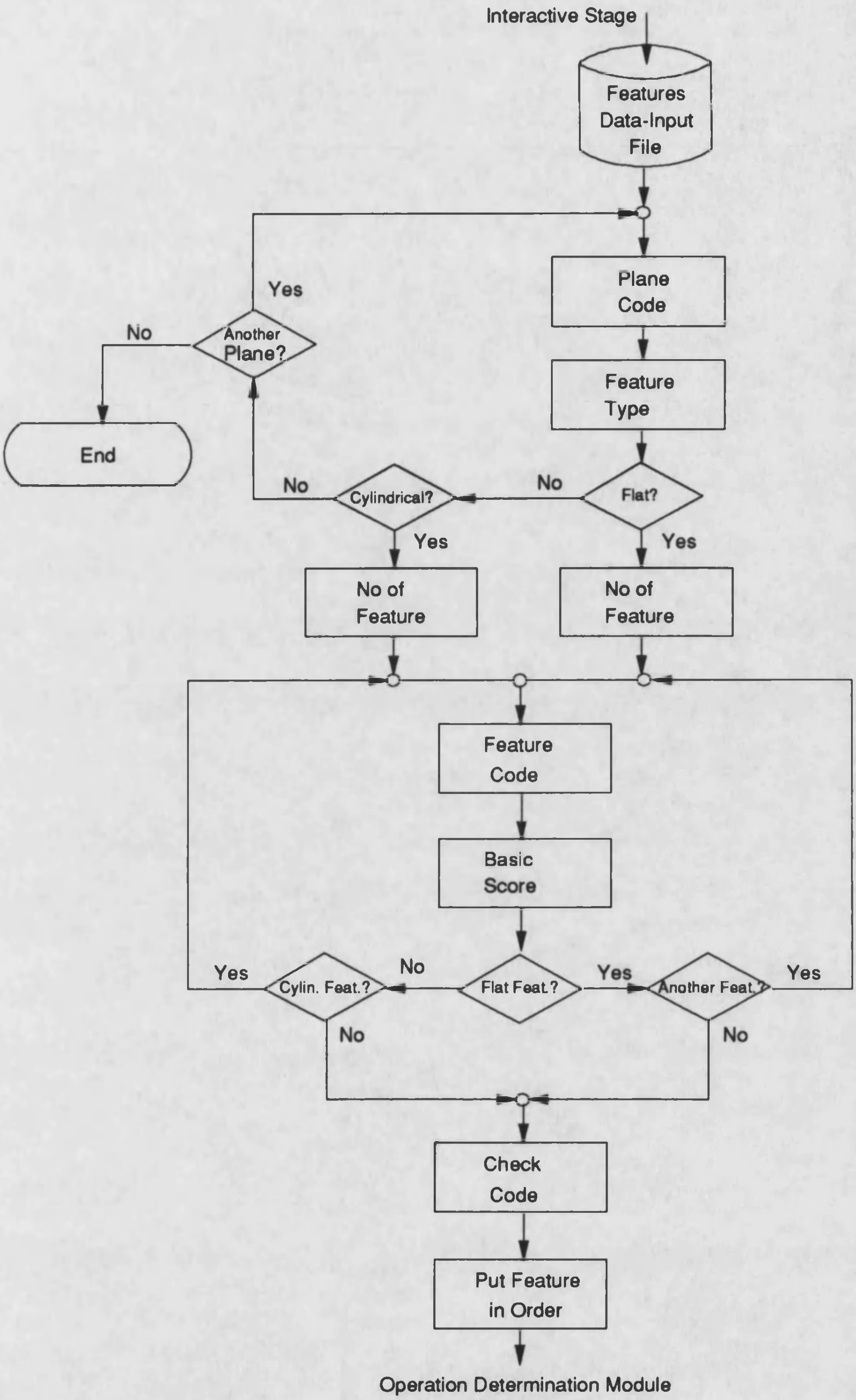


Figure 5.5: Scoring Technique Structure

ordering more effectively in further work on the system. The proposed modification would take place to the basic score value of any feature depending on it's *"priority"* for machining. The basic score can be increased depending on whether or not certain conditions are met. The logic conditions refer to such factors as feature location, finishing conditions, machinability, etc. The structure of the proposed modification technique is shown in **Figure 5.6.**

The feature ordering techniques used by BEPPS-GSCAPPP combine features of the same group together in order to give low cost by reducing undesirable non-machining time such as set-up time, loading and unloading time, etc. Also it gives the advantage of a feature order that minimises the need for different machine tools.

5.4 Automatic Operation Determination and Sequencing Module

Once feature data have been edited into the correct order for processing, the operations to produce them must be defined and sequenced. The aim of this module is to select the applicable operations for each feature. Flat features are planned for processing on milling machines and a surface grinder and cylindrical features are planned for processing on drilling, boring and internal grinding machines.

5.4.1 Operations Classification

The operations are divided into two groups: *Machining* and *Non-machining* operations. The non-machining operations include machine tool set-up, loading and unloading, cleaning and quality checks.

The machining operations are subdivided according to their capability, into *rough* and/or *semifinishing* operations and *finishing* operations. The rough and/or semifinishing operations can be typically carried out on standard milling, drilling and boring machines whereas the finishing operations are carried out for example, on grinding or honing machines where a high precision can be achieved.

5.4.2 General Consideration For Machining Operations

As discussed previously, BEPPS-GSCAPPP deals with the operations required for flat and cylindrical features on each plane separately. The following sections describe the general considerations used for rough or semifinishing operations and finishing operations for all feature types.

5.4.2.1 Rough and Finishing Operations for Flat Features

Material can be removed in a variety of ways in order to produce a particular flat feature. Therefore, various combinations of machining operations could also be used. For example, the component in **Figure 5.7-A** shows the profile of the flat features required and the different ways that they can be generated. These differences can be grouped into three mathods: (1) ***Vertical Partition Method*** (VPM), (2) ***Horizontal Partition Method*** (HPM) and (3) ***Mixed Partition Method*** (MPM).

(1) The vertical partition method produces flat features by removing the material directly above each feature as shown in **Figure 5.7-B.**

(2) The horizontal partition method produces flat features by removing the material in horizontal strips as shown in **Figure 5.7-C.**

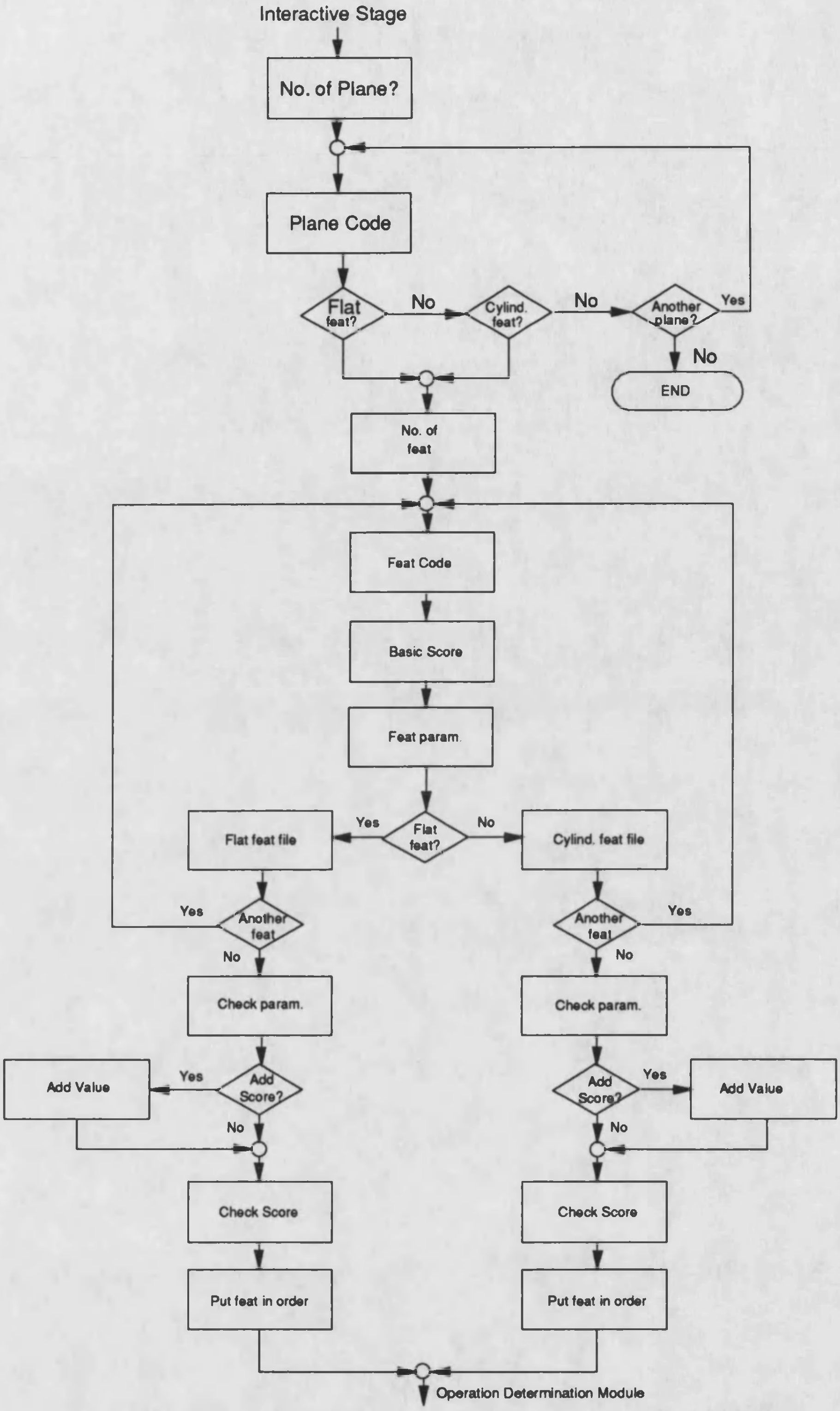


Fig 5.6: Modified Scoring Technique Structure

(3) The mixed-partition method produces flat features using a combination of the vertical and horizontal method to remove the material. Many cmbinations can be derived using this method and three examples are shown in **Figure 5.7-D.**

*Examples of how these can be machined are given in **Figure 5.8***

A computer-based exersice has been carried out to calculate the different machining times for the three methods for several components. The concept of this experiment was to find the most applicable method to adopt and relate these to both horizontal and vertical milling machines and the appropriate cutting tools. The results gave the following advantages for the horizontal method over the other two [5]:

1. Machining time is lower (typically 55%).
2. It is compatible with Top-To-Bottom feature ordering technique.
3. It allows easier planning of the machining sequence.

Therefore, the horizontal partition method has been utilised in the system to produce flat features and hence the feature order.

Rough or semifinishing operations for flat features are planned to be produced on milling machines. There are two main types of milling machines: Horizontal and Vertical.

Milling operations are produced on a horizontal mill by *peripheral milling*. Peripheral milling is an operation which is used to generate vertical and horizontal

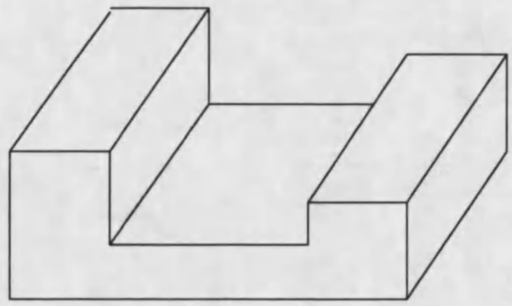


Figure 5.7-A: A Component Showing Flat Features Profile.

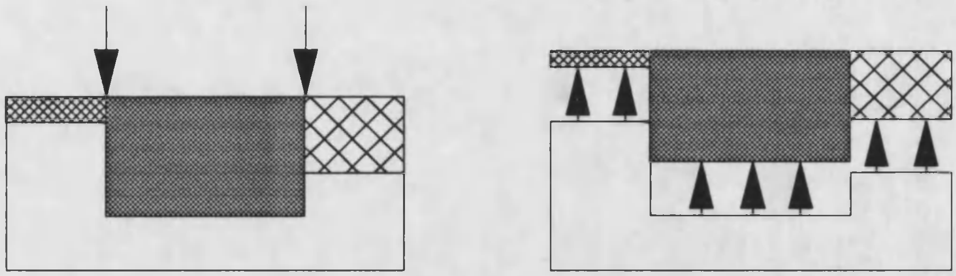


Figure 5.7-B: Vertical Partition Method.

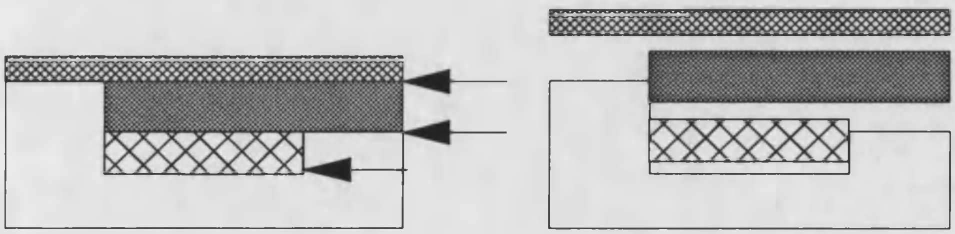


Figure 5.7-C: Horizontal Partition Method.

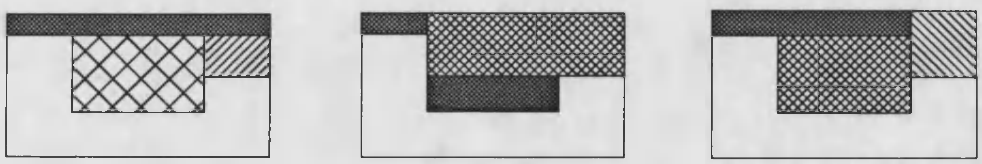
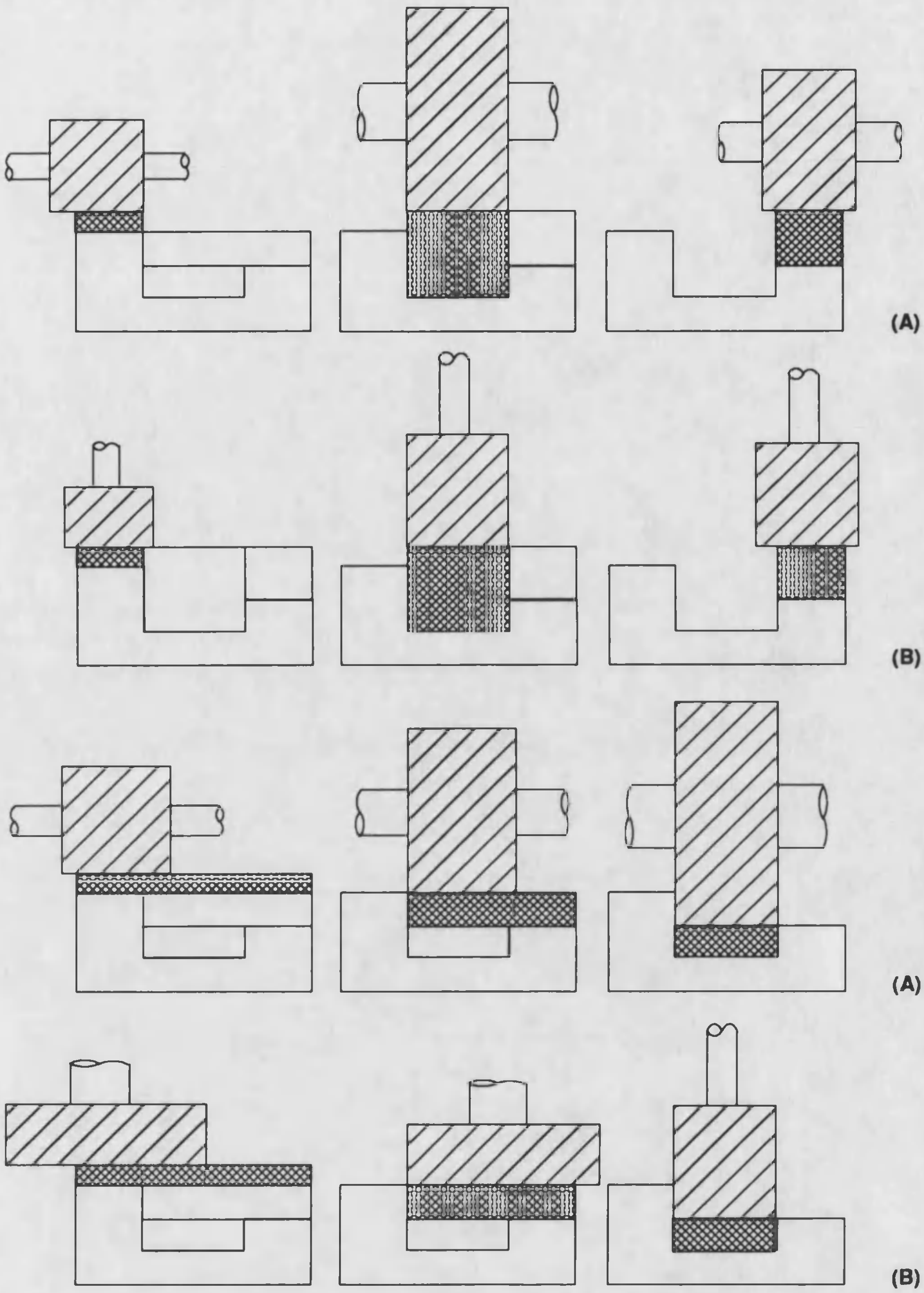


Figure 5.7-D: Examples of the Mixed Partition Method.



1. Vertical Partition Method (A) Features machined on horizontal milling machine.
(B) Features machined on vertical milling machine.

2. Horizontal Partition Method (A) Features machined on horizontal milling machine.
(B) Features machined on vertical milling machine.

Figure 5.8: Examples showing how flat features can be machined.

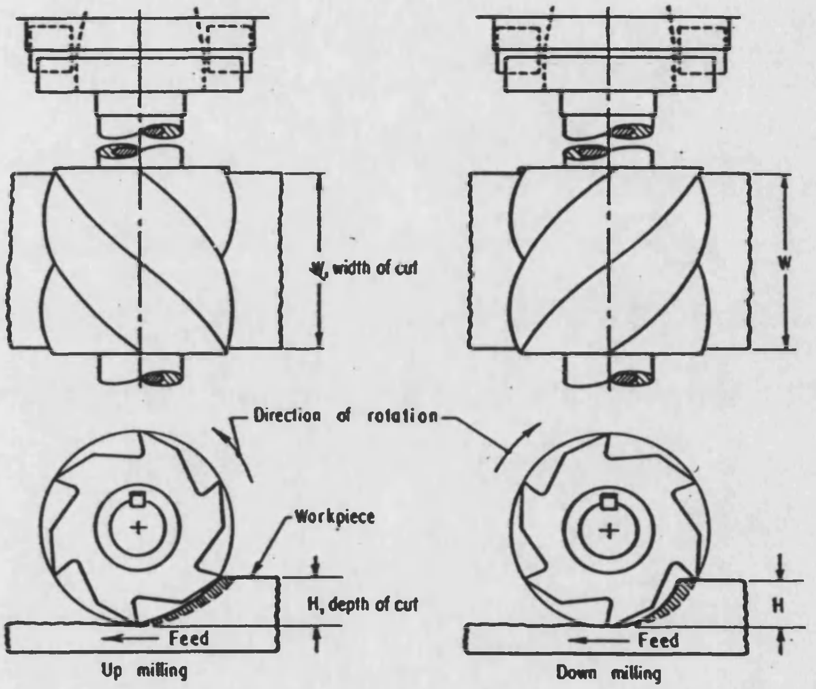
surfaces on a workpiece. Milling operations in this category include: slab milling, side and face cutting, etc.

Two types of peripheral milling are derived from the relation of cutter rotation and feed direction [54]. If the workpiece has been fed in the opposite direction to the tool rotation, then the operation is called *"climb"* milling, and if the feed direction is in the direction of the tool rotation, the operation is called *"conventional"* milling (see **Figure 5.9**). As suggested in published books, the forces and power consumption are less in climb milling than in conventional milling. However, high rigidity of both the machine tool and the work and tool holding devices are required for this operation. Due to the limited number of machine tools in the system, only climb milling is considered.

Vertical milling machines also produce flat surfaces. They are capable of machining all operations that can be produced on a horizontal milling machine. Milling operations in this category include: end milling, face milling, slot milling, etc.

The main advantages of face milling over peripheral milling are [59]:

1. Removes material with less power.
2. The cutter is more rigid.
3. Cutting forces are more evenly distributed.
4. Large areas can be machined with little protrusion of the spindle.
5. Surfaces are inherently flatter.



"climb" milling *"conventional"* milling

Figure 5.9: Climb and Conventional Milling.

The surface grinding machine is selected for finish machining operations on flat surfaces which require high accuracy and/or a good surface roughness. A fixed stock allowance is left on the feature whenever a finishing operation is required.

The factors that influence the selection of machining operations for features produced on milling machines are:

1. Feature specification.
2. Machine availability.
3. Rigidity of the machine
4. The machine used in the preceding or next operation.
5. Cutting tool (material, size, etc.).
6. Workpiece material.
7. Cutting conditions (feed, speed and depth of cut)

   a. Feed rate: This is limited in milling according to the strength of the cutting edge, machine tool rigidity, available power, cutting tool strength and surface finish required. Recommended feed rates are discussed later.

   b. Cutting speed: This is normally chosen to maintain recommended preipheral cutting conditions. A full discussion on the optimum selection of cutting speed is introduced later.

   c. Depth of cut: This is assigned according to the maximum amount of stock to be removed. If the maximum stock can be removed in one pass, then depth of cut = max. stock. When all of the stock cannot be removed in a single pass, multiple passes will then be determined.
8. Cutting time.

The selection of machining operations for flat surfaces in BEPPS-GSCAPPP takes into account special measures in order to minimise the machining and non-machining times, and hence total cost. These special measures are summarised in the following steps:

Step 1: Identify the surfaces where machining is required and check their dimensions (length, width and depth) and finishing requirements (tolerances and roughness). Note that the dimensions of any flat feature on a totally constant plane are edited according to the uniformity of the plane profile i.e. the direction in which the plane profile is uniform is considered as the length of the feature. This consideration is very important in order to determine a best operation sequence.

Step 2: Check for finishing requirements and reduce the depth by the finishing allowance where necessary. Finishing allowance value differs from operation to operation. For example, the finishing allowance for reaming is 0.4 mm.

Step 3: Select the appropriate cutting tool type and size for both vertical and horizontal machines.

Step 4: Calculate the number of cuts, the number of passes and the cutting conditions required for each feature. If the cutting tool size selected is larger than the width of the feature, then the number of cuts is equal to one. If the cutting tool size selected is smaller than the width of the feature, then more than one cut is required to produce the feature. The number of passes is determined according to the depth of the feature. For milling operations, depth of cut is restricted to the maximum limit that has been set for each machine tool depending on its power, feed and speed rate available in addition to the surface area required to be machined. The maximum depth of cut for all milling operations is fixed at 8.00 mm except for end milling in which a maximum depth of cut equal to half the cutter diameter is used [22].

Step 5: Compare the machining time for cutting tool sizes selected at step 2 and check for the minimum operation time for both the horizontal and vertical milling machines. If any non-machining operations are involved, then the times for the non-machining operations are also considered.

Step 6: For the finishing operations identified in step 2 determine the applicable operation together with the cutting conditions. Finishing operations could be achieved by milling machines if the surface quality required is within the limit of their capabilities taking into consideration the cutting speed, feed and depth of cut. Alternatively, if the surface finish required can not be achieved by milling, then surface grinding is planned by the system. At present this is the most accurate process in the system database.

Figure 5.10 illustrates the structure of machining operation selection for flat features.

5.4.2.2 Rough and Finishing Operations for Cylindrical Features

A set of machine tools have been selected for machining cylindrical features. As discussed earlier, the plain hole is the basic feature in this group. Therefore, to produce any other cylindrical feature (for example a stepped hole) the basic feature has to be considered first.

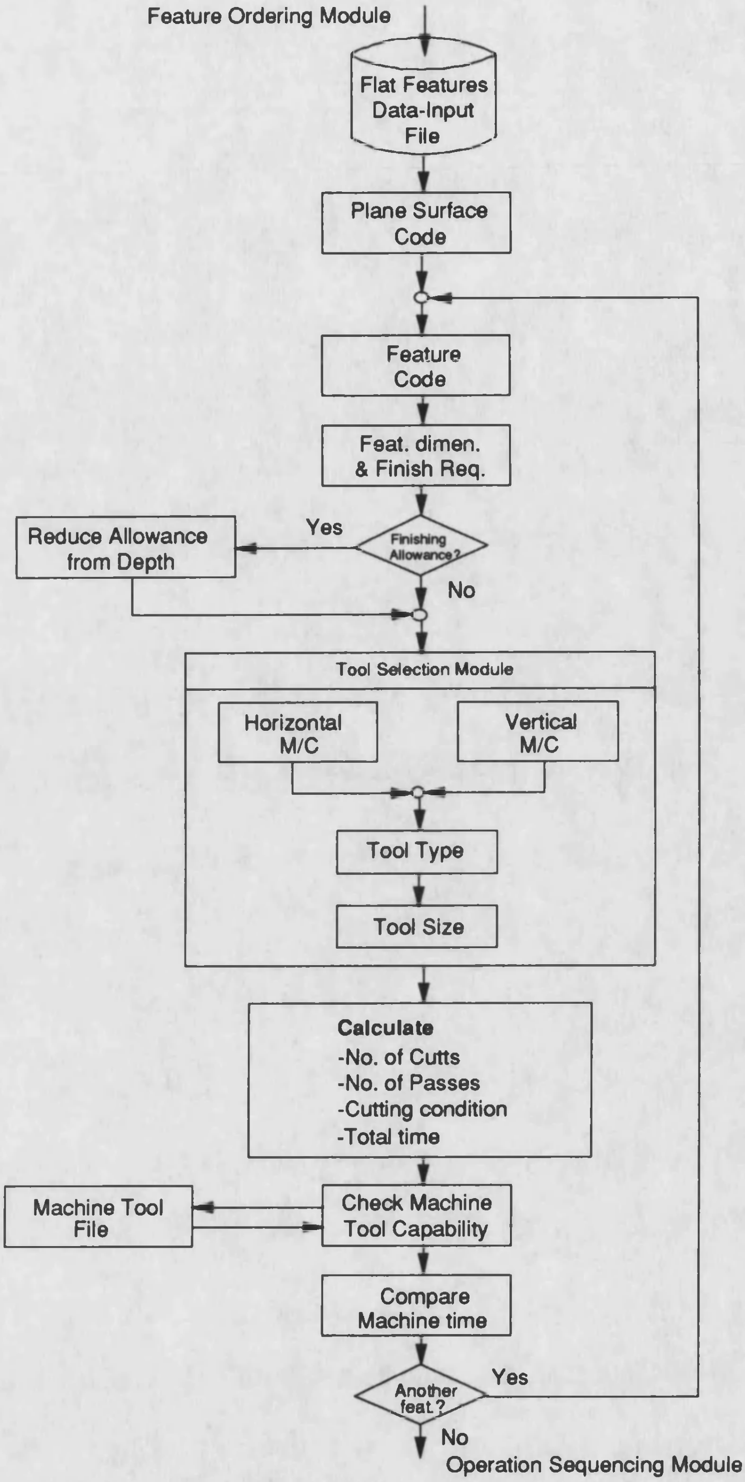


Figure 5.10: The Structure of Machining Operation Selection for Flat Features

The machining operations which have been used to machine the cylindrical features are divided into three stages: ***(1) Preparatory Stage***, ***(2) Intermediate Stage*** and ***(3) Finishing Stage.***

(1) The *preparatory stage* is the stage in which primary operations (those common to all cylindrical features) are planned ready for the next stages. These primary operations are centre drilling and drilling. From a survey of industrial practice [5] and other case study investigations, centre drilling is used in almost all cases in order to achieve accurate positioning. This is followed by a drilling operation to make an initial hole, which if accuracy is not critical or the hole is not too large, is sufficient to produce the feature. The set of drill types and machine tools that have been selected to generate holes are discussed in the following sections. In this stage, machining processes for features can be completed if feature size, finishing requirements and accuracy are within the cutting parameter limits.

(2) In the *intermediate stage* the planned operations are used to enlarge or finish holes in which the specification cannot be achieved in the preparatory stage. The intermediate stage operations include reaming and boring.

Reaming is a machining operation in which a rotary tool takes a light cut to improve the accuracy of a round hole, and to reduce the roughness of the hole's surface. Reaming accuracy is +/- 0.01 mm for diameters up to 12.00 mm and +/- 0.037 for diameters up to 25.00 mm. A material allowance of 0.4 mm on hole diameter is normally used to allow reaming to take place and the drill size is automatically reduced to accommodate this.

Boring is a machining process in which internal diameters are generated in true relation to the centre line of the spindle by means of a single-point cutting tool. It provides a better hole accuracy and surface finish than drilling as well as being capable of producing holes of larger diameter which are not usually produced by drilling. Maximum depth of cut for rough boring is 0.5 mm off the diameter.

(3) In the *finishing stage* the final dimensions for a high accuracy and/or fine finish are obtained by the use of internal grinding. The efficiency of internal grinding machines for grinding holes to close tolerances and fine finishes depends on the amount of stock to be removed and an allowance of 0.25 mm is fixed for rough grinding, 0.10 mm for semi finishing and 0.05 mm for finishing. This is reflected in the size of hole produced in the intermediate stage. Note that honing is not included as yet in the system.

The selection of machining operations for cylindrical features depends on the cutting parameters for each stage. These cutting parameters include: maximum and minimum tool size, dimensional tolerance, true position and surface finish. Other parameters such as: straightness, parallelism and roundness are not as yet considered in this work. The flow logic for operation determination for hole production is shown in **Figure 5.11.**

5.4.3 Machining and Non-machining Operations Sequencing Strategies

The BEPPS-GSCAPPP rule-based system includes a special module to control the sequencing of the machining and non-machining operations. This operation-sequencing module structure is shown in **Figure 5.12.** It describes the flow of information from the operation-determination module used to plan the

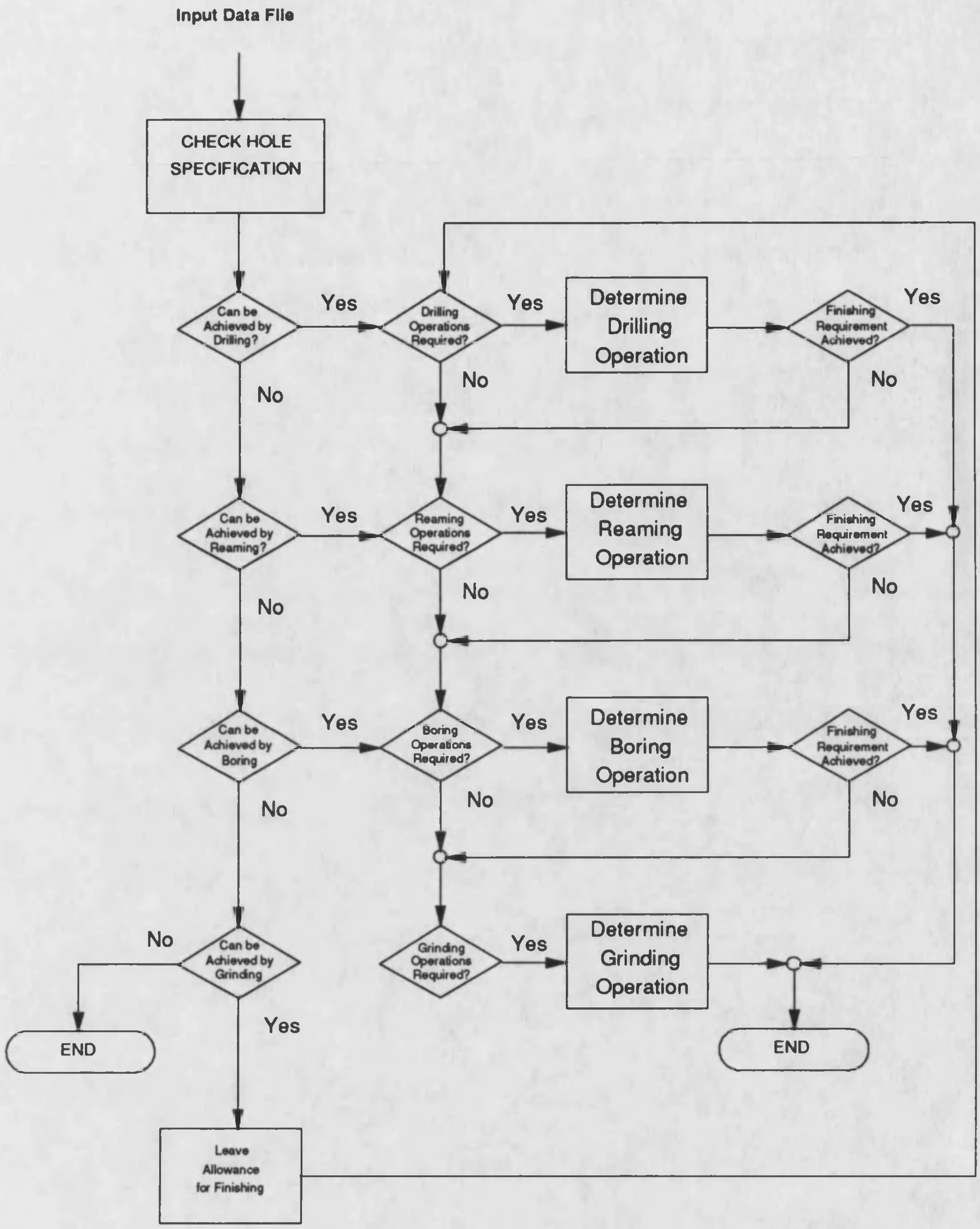


Figure 5.11: Operation Determination Flow Logic for Hole Production.

sequence of machining and non-machining operations. For each machining operation it decides which non-machining operations (at present only set-up and tool change are identified in the system) are required and then integrates them with the machining operation. This module takes into account whether the machining operation is rough, semifinishing or a finishing operation. It also considers (1) whether there are other identical operations, (2) if the same cutting tool is used elsewhere, (3) if the same machine tool is used and (4) the type of non-machining operations required (set-up, load/unload, etc.).

5.5 Automatic Machine Tool Selection Module

A set of machine tools is selected from the machine tool database that can produce both the flat and the cylindrical feature types required. The selection of the machine tool set is based on the machine tool specifications and their machining capabilities.

5.5.1 Machine Tool Database

The machine tool database file contains seven different machine types. These machines are stored in two main sub-files according to their shape generating capability: ***(1) Surface Machine Tool File*** (SMTF) and ***(2) Cylindrical Machine Tool File*** (CMTF). Machines in each file are also classified according to their surface-quality and finishing capability.

(1) Surface Machine Tool File (SMTF) includes three different machines which are capable of producing flat horizontal and vertical surfaces. These machines are classified depending on their surface-finishing capability into two groups: *(a) Standard machine type* and *(b) Precise machine type.*

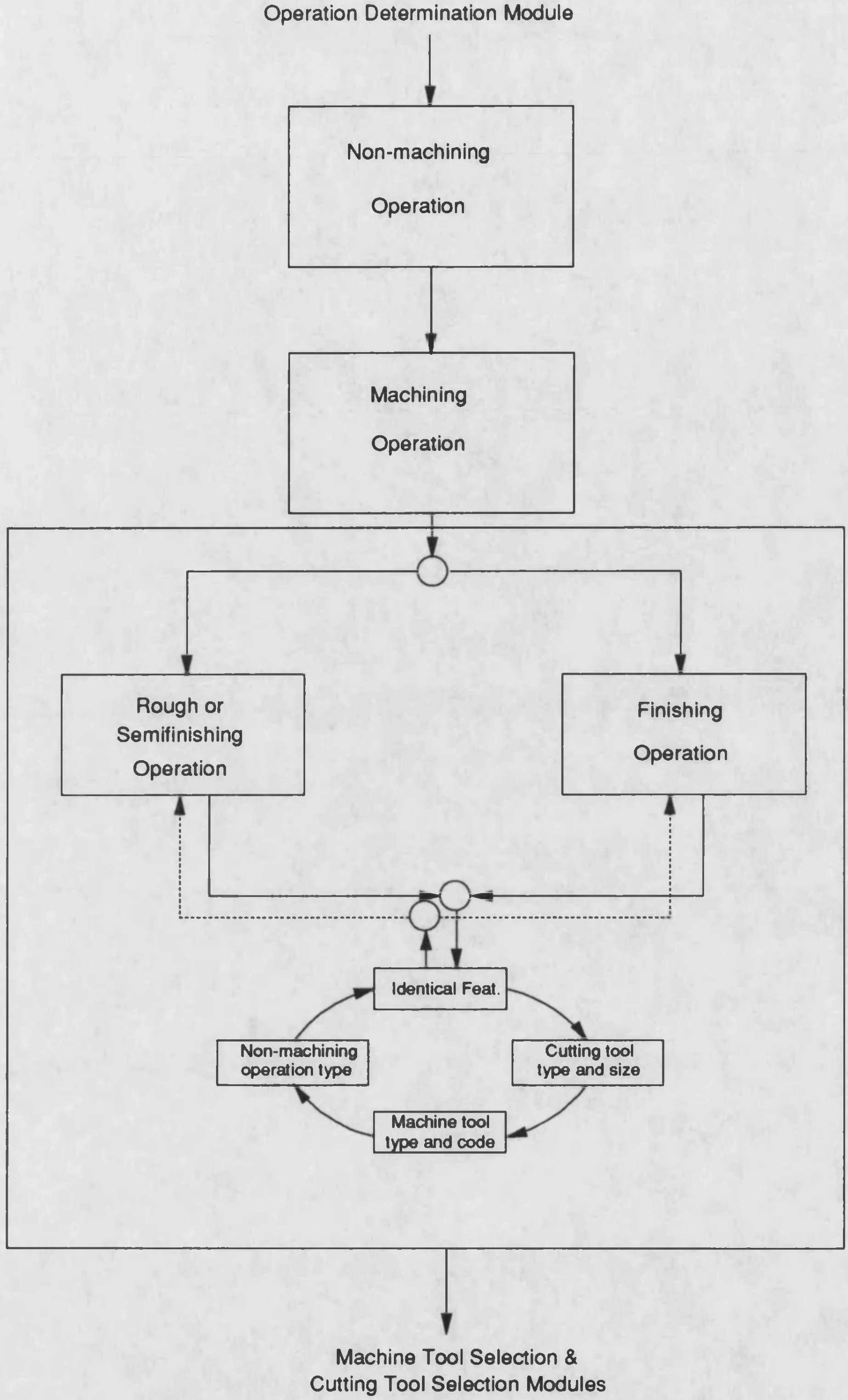


Fig 5.12 Structure of Operation Sequencing Module.

The standard machine type includes: horizontal and vertical milling machines. This category of machine tools are capable of producing flat features with a lower precision and quality of finish than the other group.

The precise machine type includes: a surface grinder which is able to machine flat surfaces of high tolerance and finish.

(2) The *Cylindrical Machine Tool File (CMTF)* contains four machines selected to produce the cylindrical type features. The four machines are classified into three types: *(a) Low precision machine type, (b) Medium precision machine type* and *(c) High precision machine type.*

The low precision machine type represents a set of machine tools which produce cylindrical features that require low dimensional tolerances and surface finishes. Machines that are selected for this category are pillar drill and radial drilling machine.

A vertical boring machine is assigned to the medium precision type which can produces cylindrical features with higher precision than that indicated in the first category.

Operations which require high precision can be produced on the internal grinder which has been selected to represent the high precision machine type.

5.5.2 Considerations for Machine Tool Set Selection

As the machine tool database file for BEPPS-GSCAPPP is divided into surface and cylindrical machine tool types, the selection of a machine tool set for any component generally depends on the factors that have been suggested by Koenigsberger and Debarr [48]. These factors include elements related to the component design such as: component size, geometrical shape, dimensional accuracy, surface finish requirement, feature types and the number of operations required to machine the component. Additional to the component design elements, the production quantity (batch size) and machine tool capacity and capability (feed, speed and horsepower and accuracy) together with the total machining cost are also considered at the initial stage of machine tool selection.

In addition to factors mentioned above, the availability of the machine tool is also important in making a positive decision to select the most suitable machine tool set. Suitability of the machine tool is also classified by Chryssolouris [15] into ***Geometrical*** and ***Technological*** factors.

1. The *geometrical factors* are concerned with the general shape envelope and size of the component as well as the component type. These factors are sufficient to choose the appropriate machine which would be able to accommodate the component.

2. The *technological factors* are related to the machine tool functional capabilities that are used to determine the machining processes for the component.

The design of BEPPS-GSCAPPP in terms of component size is limited to a maximum component size of 400 by 400 by 200 (mm), and the raw material selection module has been also devised to accept components up to this size. Hence, the machine tools selected for the system are capable of accommodating all raw material sizes identified by the raw material selection module. Also the production type (discrete or continuous) and the batch size are important for this machine tool selection process, but because of the limited variety of machines, this is not considered as yet by the system. In general geometric factors are not used in this module as much as technological factors.

The major considerations in the selection of the machine tool type in BEPPS-GSCAPPP are the functional capabilities of the machine. The functional capabilities can be tested by examining the maximum capability of the machine tool compared to the component design i.e. by testing its ability to produce as many machining operations as possible.

Machine tool rigidity and accuracy are also important in achieving the finishing requirements of a given component. If a critical tolerance or/and surface finish are required, then either one, two or more machines will be necessary to accomplish the job. For example, if a tight dimensional tolerance is required on a hole, then a drilling machine is essential to start with, and thereafter a boring machine is required to achieve the tolerance. Furthermore, if the same hole requires a high-grade surface finish that cannot be achieved by the boring machine, then an internal grinder must be added to the machine tool set. Other machine tool parameters are also used to select the machines such as: power, feed and speed range. These parameters are discussed in the cutting conditions section.

5.5.3 Automation of Machine Tool Selection Module

The appropriate machine tool set is selected automatically by the system, taking into account the factors discussed in the previous section. Once the planner or production control engineer deletes machines from the database that are involved in other jobs, the system reviews the machine tool database and brings up the available machines for the selection process. The selection process occurs separately for the surface and cylindrical machines and takes place after all input data is completed. The following describes the general steps for the machine tools selection process for both flat and cylindrical machine types:

Step 1: Check the number of features required on all of the component's planes. For example, the number of cylindrical features is needed to decide between a pillar or a radial drilling machine. The radial drill is preferred if a large number of holes are required providing the other factors are still satisfied.

Step 2: Consult with the machining operation module to verify the critical tolerances, accuracies and surface finishes required, in order to choose the machines capable of producing these critical elements.

Step 3: Specify the possible machine tool set to perform the job. At this stage machines that are able to achieve all machining processes (rough and finishing operations) have to be specified.

Step 4: Examine the technological factors on specified machines. The program evaluates the finishing requirements against the capability of the machines specified at step 3.

Step 5: Select a machine tool set that provides the optimum machining cost (as defined by the machining operations module and the cutting condition module).

5.6 Automatic Cutting Tool Selection Module

Generally, the selection of a proper cutting tool depends on the machining operations necessary for processing the feature with regard to its size and finishing requirements. Each machining operation is assigned a tool type. From the tools available on the market, a selection of different tool types and sizes have been selected and stored in the system's cutting tool database file. They have been selected to cover the needs of the component features to be processed and the machine tools used. In general, tool information supplied by SANDVIC [68] and PRESTO [62] has been identified for use in the system. The system utilises both high speed steel (HSS) and carbide cutting tools.

5.6.1 Cutting Tools Database File

The cutting tool database file **(CTF)** in BEPPS-GSCAPPP is divided according to the shape and cutting characteristics of the cutters into: ***(1) Surface Cutting Tool File*** (SCTF) and ***(2) Cylindrical Cutting Tool File*** (CCTF). Each of these categories includes different types and sizes of cutting tool.

(1) Surface Cutting Tool File (SCTF) consists of cutting tools which are selected to produce vertical and horizontal surfaces. This file is organised according to machine tool type. It is divided into three sub-files: i. Vertical milling cutting tool file **(VMCTF)**, ii. Horizontal milling cutting tool file **(HMCTF)** and iii. Surface grinding cutting tool file **(SGCTF)** which is not in use at present. A restricted cutting tool set is stored in each file.

Cutting tool types stored in (HMCTF) are: plain mills and side and face cutters. Note that other types of horizontal milling cutters such as: convex and concave cutters, etc are not considered. Also light-duty and heavy-duty plain cutters are not considered in this research.

VMCTF includes: standard face mills and end mills of different sizes which are able to cover the sizes of the flat features required.

(2) Cylindrical Cutting Tool File (CCTF) is also divided into three sub-files according to the machine tool set selected for the cylindrical features. i. Drilling tool file **(DTF)**, ii. Boring tool file **(BTF)** and iii. Grinding tool file **(GTF)**.

DTF contains different types of drills of various sizes. These include centre drills, pilot drills, twist drills, countersink drills, counterbore drills, reamers and taps. Also different sizes of boring bars and internal grinding tools are included in (BTF) and (GTF) respectively.

To enable the program to select the appropriate cutting tool size, a control file has been designed to direct the system to the right file. This direction takes place with regard to the machining operation code, feature dimensions and finishing requirements.

5.6.2 Considerations of Cutting Tool Selection

The selection of the appropriate cutting tool type and size for both types of feature (Flat and Cylindrical) is influenced by four main constraints: *(1) Machining Processes Constraint, (2) Feature Dimensions Constraint, (3)* *Machinability Constraint* and *(4) Economic Constraint.* These constraints are used for the selection of the proper cutting tool and are summarised in the following stages:

Stage 1: Retrieve the machining operation code and check the possible cutting tool types that can be used. As indicated earlier every machine tool type is assigned a set of cutting tools that can produce the specified operations. Note that at this stage the machine tool is already selected, therefore, the search for the appropriate cutting tool type and size is concentrated on cutting tool files which are related to the selected machine. More than one machine tool might be selected for the same operation depending on the feature types, sizes and finishing requirements. The alternatives are evaluated later to determine the most effective method.

Stage 2: Check the feature dimensions to retrieve the cutting width in order to search for the applicable cutting tool size from the tool list in the files indicated in stage 1. Tool size for all of the flat-feature operations might be bigger than the feature width except for slots and pockets. Therefore, this factor is taken into account at this stage to ensure the selection of the proper tool size especially for slots, pockets and cylindrical features. Also the possibility of using the same tool for other features is examined at this stage.

Stage 3: If more than one tool type is involved, the system determines the cutting conditions for the selected cutting tools.

__Stage 4:__ Calculate machining and non-machining times taking into account all cutting parameters such as number of cuts and passes for flat features. The total time is used to choose the appropriate cutting tool type and size.

If only one cutting tool type is found to machine the feature, the system adopts this as the final solution.

5.6.3 Automation of Cutting Tool Selection Module

The considerations discussed in the previous section are formed into several decision logic rules. These rules are stored in the cutting tool selection file in order to manipulate the input data file and other process planning modules to select the most appropriate tool type and size and to check if the same tool is to be used for more than one feature within the one set-up. An example of the tool selection logic rule for flat surface operation is presented below:

__A: Selection of cutting tool type__

```
IF(OPCD.EQ.'FLAT'.AND.HMLA.EQ.'Y'.AND.VMLA.EQ.'Y')THEN
    TLNM = 'PLAIN MILL CUTTER'
    TLCD = 'PMC'
    CALL HMCTF
    TLNM = 'FACE MILL CUTTER'
    TLCD = 'FMC'
    CALL VMCTF
    .. .. ..
    .. .. ..
```

```
ELSEIF(OPCD.EQ.'FLAT'.AND.HMLA.EQ.'Y')THEN
   TLNM = 'PLAIN MILL CUTTER'
   TLCD = 'PMC'
   CALL HMCTF
    .. .. ..
    .. .. ..
ELSEIF(OPCD.EQ.'FLAT'.AND.VMLA.EQ.'Y')THEN
   TLNM = 'FACE MILL CUTTER'
   TLCD = 'FMC'
   CALL VMCTF
    .. .. ..
    .. .. ..
```

This logic rule is included in the main cutting tool selection file. The function of this file is to direct the program to the file of the selected cutting tool type. The logic rule stated above is translated as follow:

If the operation code is flat and both the horizontal and vertical milling machines are available, then the plain milling cutter is selected, therefore, the program automatically moves to the horizontal milling cutting tool file to search for the appropriate sized tool. Thereafter, the program transfers to the vertical milling cutting tool file to select the appropriate size for a face mill cutter. If one of the milling machines is not available then the program is transferred to the cutting tool type which is related to the machine available (horizontal or vertical).

B: Selection of cutting tool size

The cutting tool size is selected according to the width and type of feature. For the flat surface feature, the system searches for an appropriate cutting tool with a width/diameter (width for plain mill and diameter for face mill) larger than the feature width, so that the feature can be machined in one cut. If no tool of width/diameter larger than the feature width can be found, then the search is continued for the nearest tool size that could machine the surface in more than one cut. The theoretical tool width or diameter is calculated with reference to the feature width as follows:

$TLWD = ((FLWD(4+1)/4p)$ where,

$TLWD$ is the theoretical tool width or diameter.

$FLWD$ is the flat feature's width.

p is the number of passes

C: Calculation of cutting conditions and machining time

Once the cutting conditions and machining time are calculated (as discussed in the following sections), the system chooses the cutting tool with the minimum machining time.

Table 5.1 lists the flat features and indicates the suitable machines and cutting tool types that can produce them. **Figure 5.13** illustrates the general structure of the automatic cutting tool selection for a slot machining operation.

Operation	Rough or Semi-Finishing					Finishing
Machine Type	Horizontal Milling Machine		Vertical Milling Machine			Surface Grinder
Tool / Feature	Plain Mill	Side & Face M	End Mill	Slot Mill	Face Mill	Surface
Flat Surface	***				***	***
Step Face		***	**	*		***
Side & Open Pocket			***	**		
Slot		**	*	***		***
Closed Pocket			***	*		

*** High Performance

** Medium Performance

* Low Performance

Table 5.1: Flat Feature Machine Tool and Cutting Tool Type Recommendation

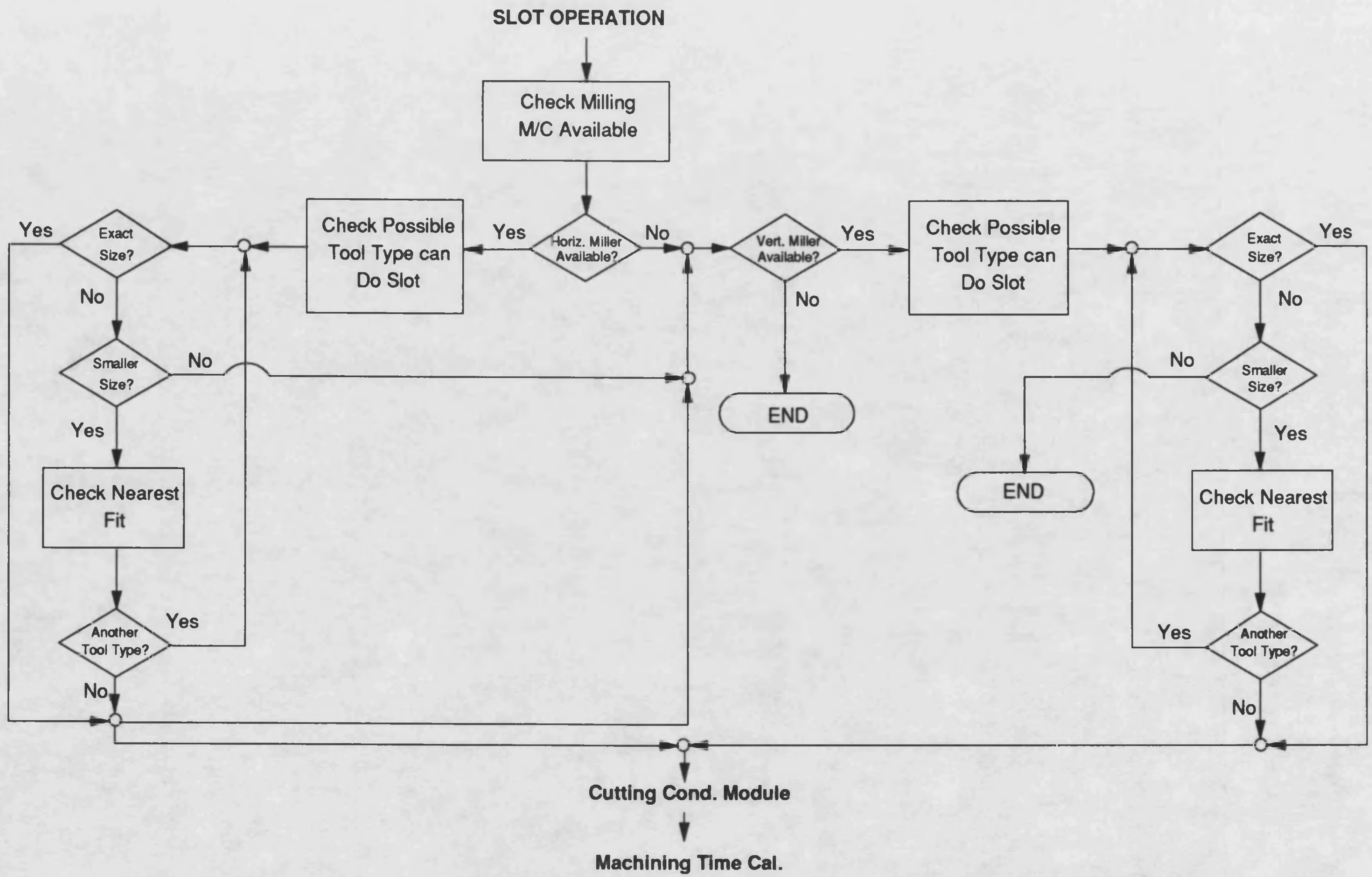


Fig 5.13: Cutting Tool Selection for Slot Operation.

Machining time is the time taken to produce a feature. It is calculated according to the cutting action of the cutter which are classified into *a. Continuous* and *b. Repetitive.*

5.7.1.1 Cutting Condition and Machining Time for Flat Features

The cutting feed and speed for the *Repetitive* cutting action processes are obtained by the same type of calculation as for the cylindrical features. The cutting time in this category varies from one process to another depending on the length of the operation. These are obtained as follows [22,54]:

a: For Slot Milling

$$T_c = \frac{L_c x n_t}{f} \qquad \textbf{(Fig. 3.14-a)}$$

b: For Face Milling

$$T_c = \frac{L_c + D}{f} \qquad \textbf{(Fig. 3.14-b)}$$

c: For Plain, Side and Open Pocket Milling

$$T_c = \frac{(L_c + \sqrt{d}\, x (D - d))}{f} \qquad \textbf{(Fig. 3.14-c)}$$

where,

T_c = Cutting Time for One Pass (min.).

L_c = Total Cutting Length (mm).

D = Diameter of Cutter (mm).

d = Cutting Depth (mm).

n_t = Total Number of Passes.

f = Feed Rate (mm/rev).

5.7.1.2 Cutting Conditions and Machining Time for Cylindrical Features

In the *Continuous* cutting action, the feed per revolution is taken as the basis for calculation. Drilling, Reaming, Counterboring, Countersinking and Tapping are in this category. The cutting speed and cutting time for this category are obtained as follows:

$$N = \frac{V x 1000}{\Pi x D}$$

where,

N = Spindle Speed (rev./min.).

V = Surface Speed (m/min.).

D = Diameter of Cutter (m).

$$T_c = \frac{L_t}{f x N}$$

where,

T_c = Cutting Time for One Cut (min.).

L_t = Total Travel Length of Cutting Tool (mm).

f = Feed Rate (mm/rev.).

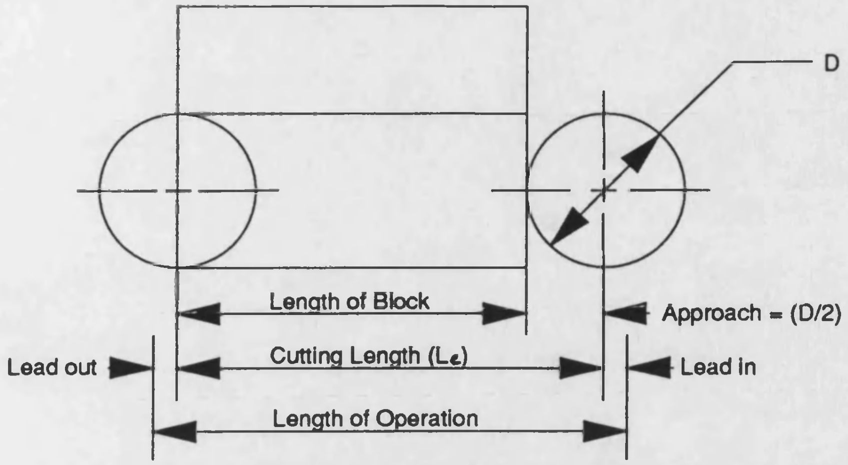
$$L_t = D_c + \frac{D}{2x\sin\left(\frac{\beta}{2}\right)} + 3$$

where,

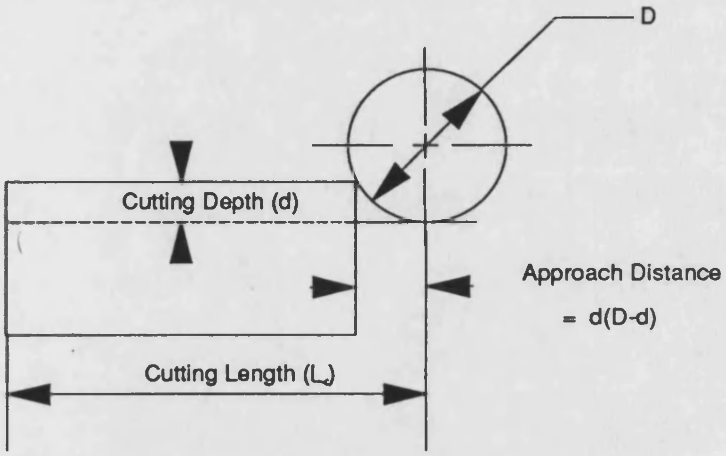
D_c = Cutting Depth (mm).

β = Cutter Angle.

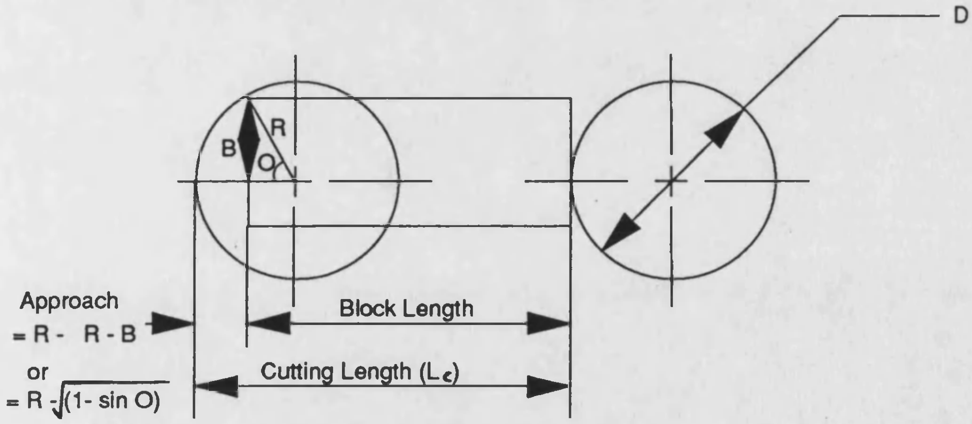
(see **Figure 5.15**)



A) Approach Distance for End Milling



B) Approach Distance for Slab or Side & Face Milling



C) Approach Distance for Face Milling

Figure 5.14: Cutting Parameters for Milling Operations.

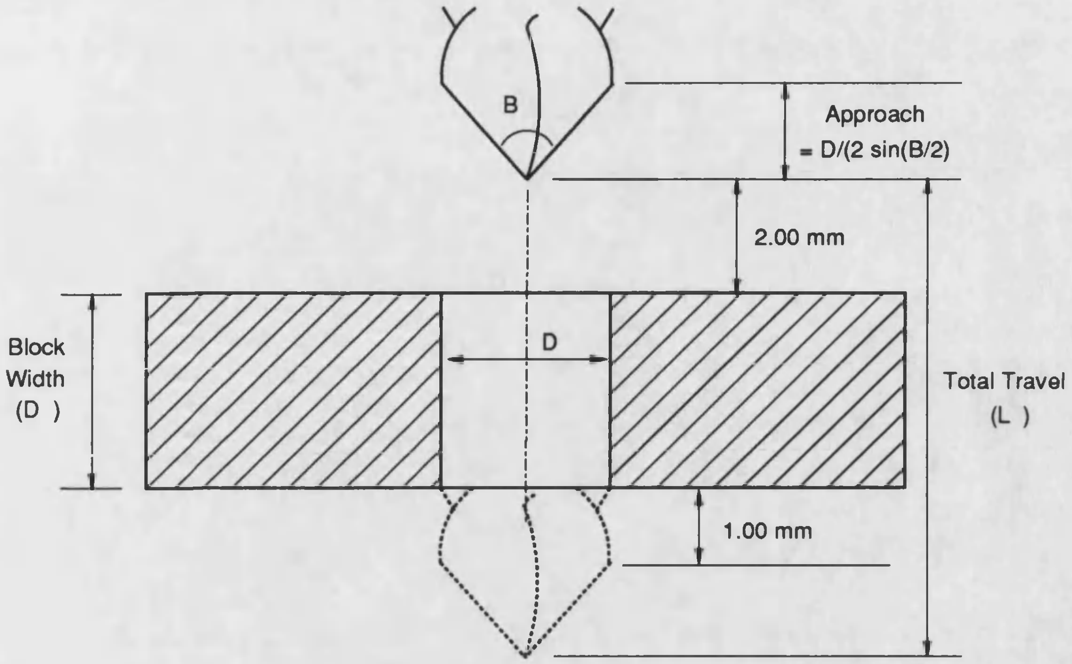


Figure 5.15: Cutting Parameters for Cylindrical Feature.

5.7.2 Non-machining Time Determination

As indicated earlier, non-machining operations include times for: a. Set-up, b. Loading/Unloading, c. Tool change, d. Feed and speed adjusting and e. Inspection. Every operation is given a fixed time according to the machine tool type at present. Further work is required to break down these times in greater detail.

5.7.3 Automatic Total Time Calculation Module

Once the machining and non-machining times are calculated, the system summarises these to give a total time for each feature.

As stated earlier, the output sheet is divided into three sections: Cut-To-Length, Flat Feature and Cylindrical Feature sections. The total time is summarised separately for each section. After the total time for each section is completed, the system summarises the total machining and non-machining times for the whole component. The total time for the batch is finally calculated.

5.8 Automatic Holding Device Consideration Module

The workpiece holding device for BEPPS-GSCAPPP in its research form is considered in outline only. The factors that should be considered for work holding are summarised as follows:

1. Workpiece size.
2. Workpiece weight.
3. Workpiece design.
4. Production system type.

5. Batch size.
6. Location surfaces.
7. Clamping.

Logical rules for the above are developed to identify whether a workpiece requires a holding device or not. The factors which have strong influence in this module are: workpiece size, workpiece weight, workpiece design, production system type and batch size.

CHAPTER (6)

BEPPS-GSCAPPP In Action

6.1 Introduction

This chapter gives a brief description of BEPPS-GSCAPPP in operation, and presents in detail the interactive input stage and the process planning sheet output. In the interactive stage it shows how the system prompts the planner to input the necessary infomation (as discussed in section 4.3) into the system and finally discusses the results of the three prismatic components that have been chosen as examples to reveal the performance of the system.

6.2 BEPPS-GSCAPPP Operation

BEPPS-GSCAPPP has been written in FORTRAN 77 and runs on a SUN workstation. In order to generate an accurate and complete plan, the planner has to be familiar with the system's operation. Before choosing the process planning option, the planner has to study the component design and can select the *User's Help* option for guidance. The following section describes the various screens and options used.

```
*********************************************************************
 Generative System of Computer-Aided Process Planning for Prismatic

             ( B E P P S - G S C A P P P  )

*********************************************************************
```

```
  ****************************************************************
  **    B E P P S - G S C A P P P     O P T I O N S     **
  ****************************************************************
  *  1) User's Help              2) Process Planning             *
  *  3) Decision Logic           4) Output Sheet Modification    *
  ****************************************************************
  Which (1,2,3 or 4)? 1
```

The User's Help option is designed to direct the planner in how to operate the system. This option provides the planner with two types of help mode: (1) *Getting Started Mode* and (2) *Component Data Input Mode.*

```
---------------------------------
 BEPPS-GSCAPPP HELP MODE OPTIONS
---------------------------------
 (1) Getting Started Mode.
 (2) Component Input Mode.
---------------------------------
Which (1 or 2)? 1
```

The getting started mode displays the guide-lines of the system and shows the planner the important steps to follow. These guide-lines and steps are shown below:

```
---------------------------------------------------
               GETTING STARTED MODE
---------------------------------------------------

PEPPS-GSCAPPP contains three main stages; Input, Au-
tomatic and Output stages. This mode is to guide you
to start using the system to input the data required
to enable the system automatically generate process
plans.

Firstly, you have to know more about the interactive
(input) stage:

- This stage consists of the following;
  1. General Information.
  2. Part and Production Information.
  3. Part Classification and Description.
  4. Machine Tools Available in the System.
  5. Feature Data Input.

Secondly, the following are important points to put
into consideration:

  1. Use upper case (capitals) all the time.
  2. Input data type as defined in front of question
     Data types are of:
       (a) Intiger represented by [Int.].
       (b) Real represented by [Rel.].
       (c) Character represented by [Chr.].
  3. Follow the remarks given.
  4. Check appendix or figure if necessary.

Help about component data input is in help mode (2).
---------------------------------------------------
 Would you like another help mode option (Y/N)? Y
```

The component data input mode explains, in steps, how the planner should input the component data. The component's data includes: the component overall dimensions, plane and edge coding, machines available, component type and features data input. The steps of this mode are detailed in the following screen displays:

```
 ---------------------------------
 BEPPS-GSCAPPP HELP MODE OPTIONS
 ---------------------------------
  (1) Getting Started Mode.
  (2) Component Input Mode.
 ---------------------------------
Which (1 or 2)? 2

----------------------------------------------------
                PART DATA INPUT MODE
----------------------------------------------------

This mode shows you how to input data in the follo-
wing important sections:

  1. Part Classification and Description.
  2. Feature Data Input.

----------------------------------------------------
 Which (1 or 2)? 1

----------------------------------------------------
   1. Help for Part Classification and Description
----------------------------------------------------

It is necessary to input data in this section corr-
ectly, so as to avoid any error in the results.

* In this section you need to input the overall dimen-
  sions of the part (X, Y and Z) considering;

  1- The longest dimension of the part to be consider-
     ed as the length.
  2- The medium dimension to be considered as the wid-
     th.
  3- The smallest dimension to be considered as the
     depth.
  4- If two dimensions are the same, then;
     a) if they are higher than the third, enter them
        as length and width or
     b) if they are lower than the third, enter them
        as width and depth.
          (The system will do this automatically)

** It is important to input the part's dimension corr-
   ectly with reference to x, y and z axis as follows;

   1- The length direction is the x-axis.
   2- The width direction is the y-axis.
   3- The depth direction is the z-axis.

*** To select the datum surface(s), you have to consi-
    der the following;

    1- Number of plane surfaces requiring machining.
    2- Feature location and tolerance.
```

```
- You have to select at least one datum surface.

  (For more explannation refer to Appendix "A")

**** Components in the system are divided into;
  1. Constant cross-section component.
                  and
  2. Non-constant cross-section component.

  (For more explannation refer to Appendix "B")
---------------------------------------------------
Would like another section (Y/N)? Y


---------------------------------------------------
                PART DATA INPUT MODE
---------------------------------------------------

This mode shows you how to input data in the follo-
wing important sections:

  1. Part Classification and Description.
  2. Feature Data Input.

---------------------------------------------------
Which (1 or 2)? 2

---------------------------------------------------
          2. Help for Feature Data Input
---------------------------------------------------

Features in the system are divided into two groups;
  1- Flat group      and      2. Cylindrical group.

Every feature in these group require defferent info-
rmation. You need to pay attention, particularly, on
the flat group features to the following points;

   1- Cutting direction.
   2- Feature ordering.

   (For more explannation refer to Appendix "B")
---------------------------------------------------

Would like another section (Y/N)? N

Would you like another help mode option (Y/N)? N

Would you like to keep the help mode in screen (Y/N)? Y

Would you want another GSCAPPP option (Y/N)? Y
```

In addition to the User's Help option, the system provides the planner with remarks to help the user during the input stage. These remarks have been placed in strategic locations to enable the planner to input the data correctly and rapidly.

6.3 BEPPS-GSCAPPP Application

This section demonstrates the capability of BEPPS-GSCAPPP by using three examples. These three examples have been chosen to represent the three types of component as classified by the system (TCX-SEC, PCX-SEC and NCX-SEC). The designs of these examples are intended to include all features adopted by the system with differing sizes. To enable the competence of the raw material selection module to be illustrated, the three examples have been chosen with different materials and sizes.

6.3.1 Example 1: Totally Constant Cross-section Component (TCX-SEC)

The Totally Constant Cross-section Component (TCX-SEC) is shown in **Figure 6.1**. The material of this component is mild steel. The overall dimensions are 100.00 X 80.00 X 45.00 (mm). It contains: a stepped face, two slots, an open pocket, a through plain hole, a blind stepped hole with a conical end and a blind countersunk hole with a flat end. The following input screens are presented to collect information.

(i) Information collected for process plan header:

```
***************************************************************
**   B E P P S - G S C A P P P     O P T I O N S            **
***************************************************************
*  1) User's Help               2) Process Planning           *
*  3) Decision Logic            4) Output Sheet Modification  *
***************************************************************

Which (1,2,3 or 4)? 2

Do you wish to plan for a:

1) New part    or    2) Old part?

WHICH (1 or 2)? 1

****************************************
     GENERAL INFORMATION DATA INPUT
****************************************

Planner's name (12 Char. max.)? E.A.RUSTOM

Date (D.M.Y)? 27 JAN 92
```

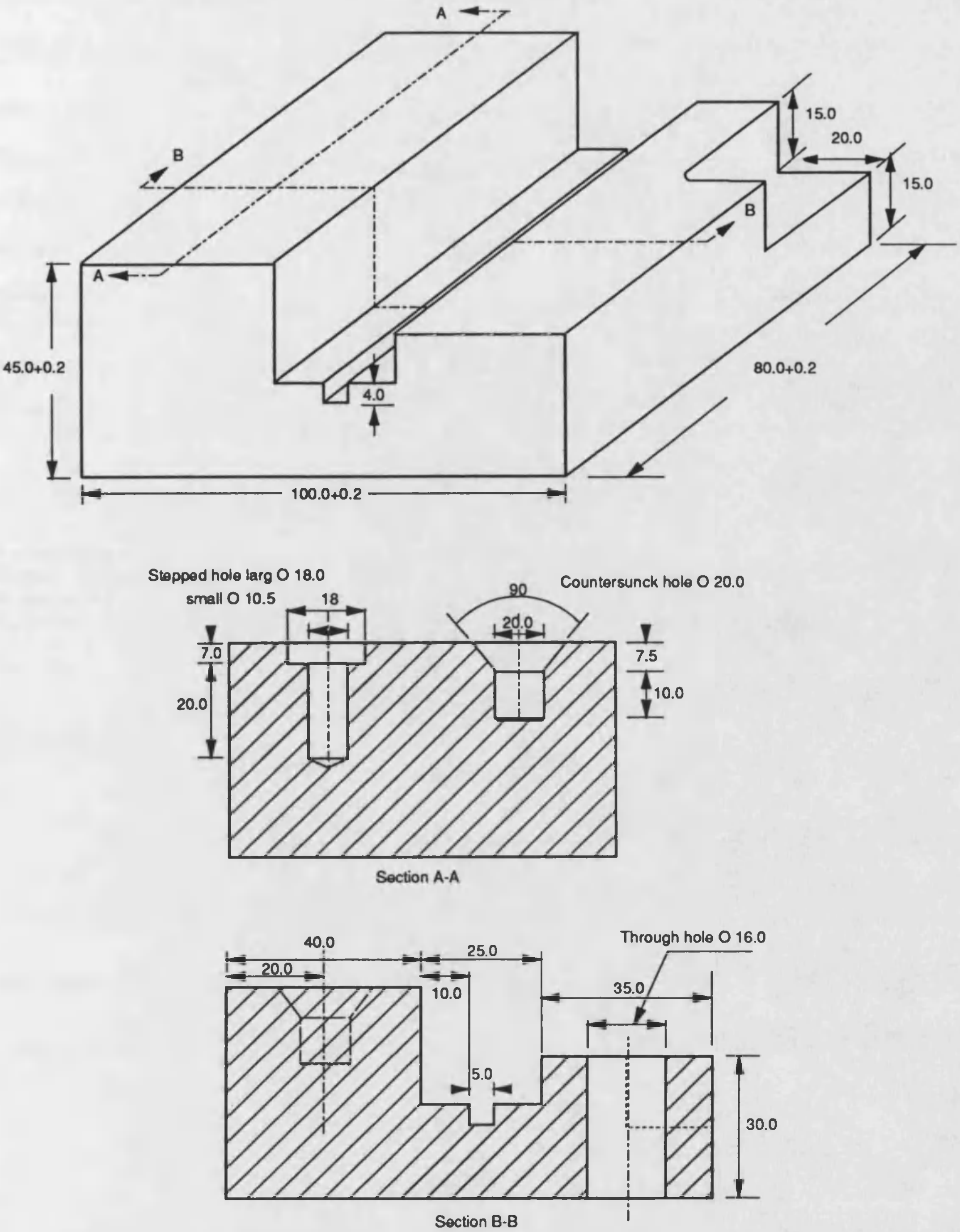


Figure 6.1: Example (1) TCX-SEC Component.

```
Part and Production Information
--------------------------------

Part name (12 Char. max.):? TCX-EXAMPLE-1

Part number (12 Char. max.):? EX00001

Drawing number (12 Char. max.):? XXXXXX

Assembly number (12 Char. max.):? XXXXXX

Demand type:
1. Discrete. or 2. Continuous.(1/2)? 2

Batch size:? 50

-------------------------------------------------------------
     II  N  N  PPP   U   U  TTTTT     DDD    OOO    CCC
     II  NN N  P  P  U   U    T       D  D  O   O  C
     II  N NN  PPP   U   U    T    .. D  D  O   O  C
     II  N  N  P      UUU     T    .. DDD    OOO    CCC
-------------------------------------------------------------
1.Planners Name : E.A.RUSTOM      2.Date :   27 JAN 92
3.Part Name : TCX-EXAMPLE-        4.Part No : EX00001
5.Drawing No : XXXXXX             6.Assembly No : XXXXXX
7.Demand Type : CONTINUOUS        8.Batch Size :   50

Is that right (Y/N)? Y
```

(ii) Interactive information used to select raw material:

```
****************************************************

     Appropriate Material Size Selection Module

****************************************************


The materials we deal with are as follow :

----------------------------------------
 MTNO      Material   Name       CODE
----------------------------------------
   1.      Mild  Steel            MS
   2.      Carbon  Steel          CS
   3.      Aluminium              AL
----------------------------------------

Is the part material one of these (Y/N)? Y

What is the part material code (MS, CS, AL)? MS


----------------------------------------------
     Part Classification and Description
----------------------------------------------

Would you like to use a standard form of material (Y)/(N)? Y
```

```
---------------------------------------------------------------------------
              For the benifit of the system pleaseconsider
              the part's overall dimensions (X, Y and Z):-
---------------------------------------------------------------------------

1- The longest dimension of the part is considered as the length.
2- The medium dimension is considered as the width.
3- The smallest dimension is considered as the depth.
4- If two dimensions are the same, then;
   a. if they higher than the third enter them as length and width, or
   b. if they are lower than the third enter them as width and depth.

   (The system will do this automatically)
---------------------------------------------------------------------------

What is the part's overall length (IN mm)? 100.

What is the part's overall width (IN mm)? 45.

What is the part's overall depth (IN mm)? 80.

-----------------------------------------
   Part's overall dimensions
-----------------------------------------
Material        Length   Width    Depth
-----------------------------------------
MILD STEEL      100.00   45.00    80.00
-----------------------------------------

Is that right (Y/N)? Y

      Overall Dimensions
-----------------------------------------
Material        Length   Width    Depth
-----------------------------------------
MILD STEEL      100.00   80.00    45.00
-----------------------------------------


----------------------------------------
 The system considers the following :
----------------------------------------
 1. The length direction is the X-axis.
 2. The width direction is the Y-axis.
 3. The depth direction is the Z-axis.

     (Please refer to Appendix "A")
----------------------------------------

 Datum surfaces selection :-
 ---------------------------
 How many datum surface(s) are required (1 TO 3)? 3

 If part has 3 datum surfaces their codes will be :

      (XD,YD AND ZD)

 -------------------------------------------------------------
      Now you required to enter the surface requirements
              for each plane surface of the part
 -------------------------------------------------------------
 Please enter the surface requirements for each plane surface
 - If no surface tolerance is required please enter (0).
 - Only flat features should be considered.
 - See Appendix "B" for more explanation.
 -------------------------------------------------------------
```

```
Tolerence required on plane surface :

   Tol. in X (mm)= .2

   Tol. in Y (mm)= .2

   Tol. in Z (mm)= .2

Roughness required on plane surface :

   XD Ruf. in (um)= 4.

   XO Ruf. in (um)= 4.

   YD Ruf. in (um)= 4.

   YO Ruf. in (um)= 4.

   ZD Ruf. in (um)= 4.

   ZO Ruf. in (um)= 4.

          Tolerence required on
  ------------------------------------------
      Length     Width     Depth
  ------------------------------------------
       0.200     0.200     0.200
  ------------------------------------------
          Roughness required on
------------------------------------------------
   XD       XO       YD       YO       ZD       ZO
------------------------------------------------
 4.000    4.000    4.000    4.000    4.000    4.000
------------------------------------------------
Is that right (Y/N)? Y

         YOUR ORIGINAL DATA IS
-----------------------------------------
MATERIAL       LENGTH    WIDTH    DEPTH
-----------------------------------------
MILD STEEL     100.00    80.00    45.00
--------------------------------------------------
      THE POSSIBLE STANDARD SIZE(S)
--------------------------------------------------

USE MS SIZE : 150.00   150.00  CODE :MS15X15
CUT TO LENGTH :    49.00

USE MS SIZE : 110.00    80.00  CODE :MF11X25
CUT TO LENGTH :    84.00

USE MS SIZE : 100.00    50.00  CODE :MF10X5
CUT TO LENGTH :  104.00

--------------------------------------------------

==================================================
        THE BEST STANDARD SIZE IS
==================================================
USE MS SIZE : 100.00    50.00  CODE :MF10X5
CUT TO LENGTH :  104.00

      (Note: All dimensions in mm)
==================================================

13.The standard size selected is larger by:
---------------------------------------------------------
          YD or YO  ,  ZD or ZO  and  XD or XO
            20.00        5.00          4.00
---------------------------------------------------------
```

Once the best standard size has been selected, the user has to consider the extra material and treat this as a feature (flat surface). The user also has to consider which planes XD or XO, YD or YO and ZD or ZO should be edited in order to achieve a good result. According to the rules indicated in Appendix (B), the user could choose either the XD or XO and the YD or YO when the weight of each is equal. For the ZD and ZO, planes however the situation is different, as the weight of plane ZO (30) is higher than the weight of plane ZD (15). Therefore, planes XO, YO and ZO are selected for machining to depths of 4.00, 5.00 and 20.00 mm respectively.

Figure 6.2 shows the TCX-SEC component (example 1) inside the standard shape envelope and demonstrates the execution steps of planes and features data input.

(iii) Information collected to define machine tool set:

```
----------------------------------
   MNO   MC NAME          MCD
----------------------------------
       1.   PILLER DRILL 1   PD1
Is it available (Y/N)? Y
       2.   PILLER DRILL 2   PD2
Is it available (Y/N)? Y
       3.   RADIAL DRILL 1   RD1
Is it available (Y/N)? Y
       4.   HORIZ. MILLING   HML
Is it available (Y/N)? Y
       5.   VERTI. MILLING   VML
Is it available (Y/N)? Y
       6.   VERTI. BORIMG    VBR
Is it available (Y/N)? Y
       7.   HORIZ. GRINDER   HGD
Is it available (Y/N)? N
       8.   VERTI. GRINDER   VGD
Is it available (Y/N)? N
----------------------------------
```

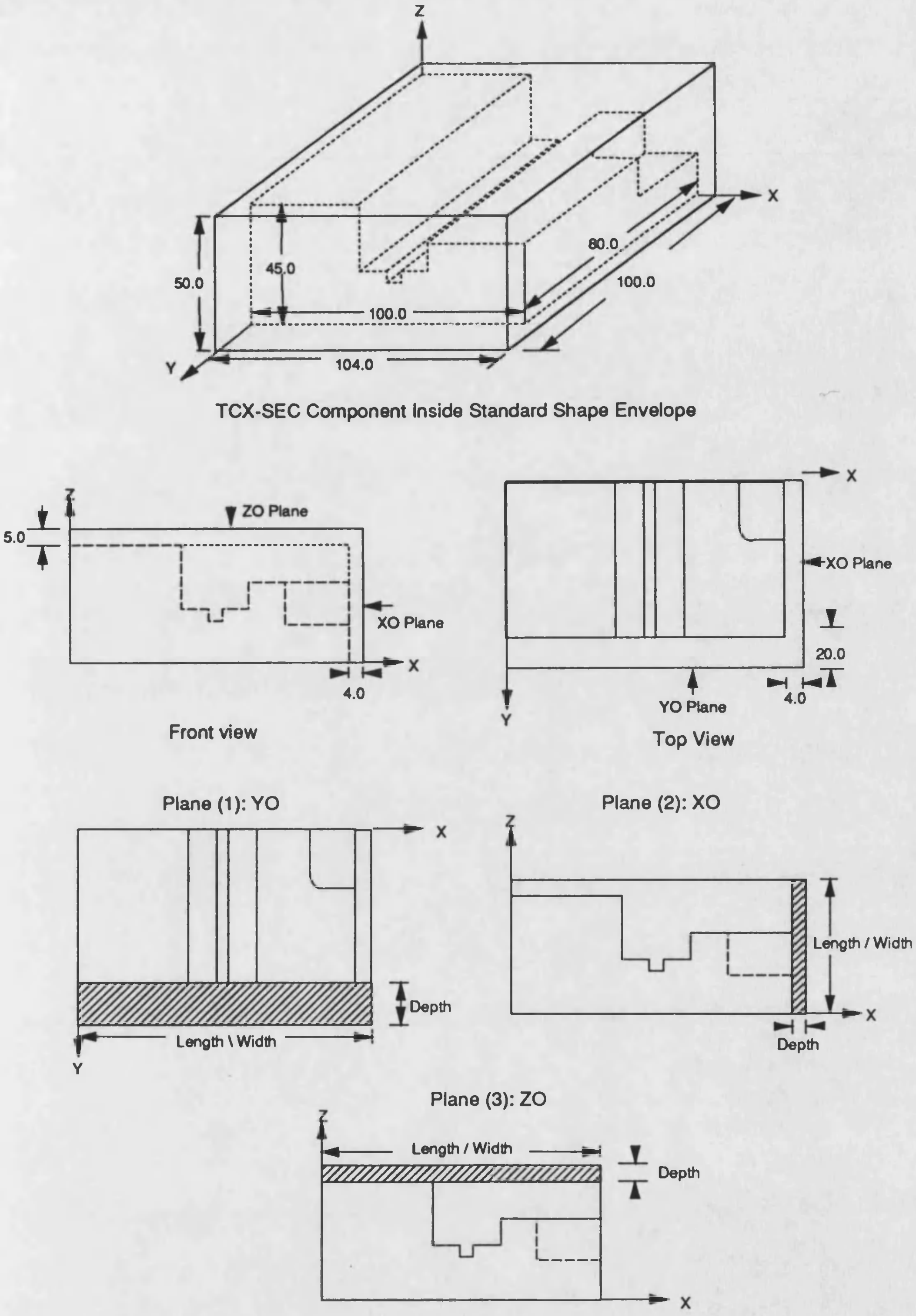


Figure 6.2: Planes Input Sequence for TCX-SEC Component.

(iv) Information collected to define component type and the number of planes:

```
Is the part of Constant x-section or Non-constant x-section (C/N)? C

How many plane surfaces require machining (1-6)? 3
```

(v) Information collected for plane 1:

```
Input Plane Surface CODE :
(XD,XO,YD,YO,ZD or ZO)? YO


**********************************

     Feature Data Input Module

**********************************


How many features on this plane?
Is it : 1- One feature?
        OR
        2- More than one feature?

Which (1 or 2)? 1

Features are grouped into Flat and Cylindrical as follow

 ---------------------------------------------
 FLAT GROUP                  CYLINDRICAL GROUP
 ---------------------------------------------
 Flat surface.               Simple hole.
 Step face.                  Stepped hole.
 Open or side pocket.        Countersunk hole.
 Slot.                       Thread.
 Closed pocket.
 ---------------------------------------------

Do you have any feature from the flat group (Y/N)? Y

---------------------------------------------------
 Flat features for constant x-section components
            includes the following:
---------------------------------------------------
      Feat. Id.                Feat. Code
-------------------------------------------------
      Flat Surface                FT
      Step face                   SF
      Side Pocket                 SP
      Open pocket                 OP
      Slot                        ST
-------------------------------------------------

What is the feature code ? FT

The feature selected is: Flat Surface

Is that correct (Y/N)? Y

Input Flat Face length (mm)? 50.

Input Flat Face width (mm)? 104.

Input Flat Face depth (mm)? 20.

Input Flat Face Roughness (um)? 4.

Code  Length  Width  Depth  Ruf.
----------------------------------
 YO    50.00 104.00  20.00 4.00
----------------------------------

Is that right (Y/N)? Y
```

(vi) Information collected for plane 2:

```
Input Plane Surface CODE :
(XD,XO,YD,YO,ZD or ZO)? XO

How many features on this plane?
Is it : 1- One feature?
        OR
        2- More than one feature?

Which (1 or 2)? 1

Features are grouped into Flat and Cylindrical as follow

----------------------------------------------
 FLAT GROUP                CYLINDRICAL GROUP
----------------------------------------------
 Flat surface.             Simple hole.
 Step face.                Stepped hole.
 Open or side pocket.      Countersunk hole.
 Slot.                     Thread.
 Closed pocket.
----------------------------------------------

Do you have any feature from the flat group (Y/N)? Y


--------------------------------------------------
 Flat features for constant x-section components
           includes the following:
--------------------------------------------------
      Feat. Id.                 Feat. Code
--------------------------------------------------
      Flat Surface                 FT
      Step face                    SF
      Side Pocket                  SP
      Open pocket                  OP
      Slot                         ST
--------------------------------------------------

What is the feature code ? FT

The feature selected is: Flat Surface

Is that correct (Y/N)? Y

Input Flat Face length (mm)? 50.

Input Flat Face width (mm)? 80.

Input Flat Face depth (mm)? 4.

Input Flat Face Roughness (um)? 4.

Code  Length  Width  Depth  Ruf.
-------------------------------------
 XO    50.00  80.00   4.00 4.00
-------------------------------------
```

(vii) Information collected for plane 3:

```
Input Plane Surface CODE :
(XD,XO,YD,YO,ZD or ZO)? ZO

How many features on this plane?
Is it : 1- One feature?
        OR
        2- More than one feature?

Which (1 or 2)? 2

Do you have any feature from the flat group (Y/N)? Y

How many flat feature in this plane? 5
```

- Information for flat feature 1:

```
What is the feature code ? FT

The feature selected is: Flat Surface

Is that correct (Y/N)? Y

Input Flat Face length (mm)? 80.

Input Flat Face width (mm)? 100.

Input Flat Face depth (mm)? 5.

Input Flat Face Roughness (um)? 4.

Code  Length  Width  Depth  Ruf.
------------------------------------
 ZO    80.00 100.00   5.00 4.00
------------------------------------
Is that right (Y/N)? Y
```

- Information for flat feature 2:

```
What is the feature code ? SF

The feature selected is: Step face

Is that correct (Y/N)? Y

Datum edge code must be one of these :
      EX2, EX3, EY2 OR EY3
Input surface datum edge code : EX3

Input surface length (mm)? 60.

Input surface width (mm)? 60.

Input surface depth (mm)? 15.

Input face roughness (um)? 3.

Input side roughness (um)? 3.

            Step face data
------------------------------------------------
 Code Edge Length Width  Depth  FR   SR
------------------------------------------------
 ZO  EX3   60.00  60.00  15.00  3.00  3.00
------------------------------------------------
Is that right (Y/N)? Y
```

- Information for flat feature 3:

```
What is the feature code ? ST

The feature selected is: Slot

Is that correct (Y/N)? Y

Edge code must be one of these :
      EX2, EX3, EY2 OR EY3
Input edge code : EX3

Input length (mm)? 80.

Input width (mm)? 25.

Input depth (mm)? 10.

Input face Roughness (um)? 3.

Input sides Roughness (um)? 3.

Code Edge Length Width  Depth  F.R. S.R.
------------------------------------------------
 ZO  EX3   80.00  25.00  10.00  3.00  3.00
------------------------------------------------
Is that right (Y/N)? Y
```

- Information for flat feature 4:

```
What is the feature code ? ST

The feature selected is: Slot

Is that correct (Y/N)? Y

Edge code must be one of these :
      EX2, EX3, EY2 OR EY3
Input edge code : EX3

Input length (mm)? 80.

Input width (mm)? 5.

Input depth (mm)? 4.

Input face Roughness (um)? 2.

Input sides Roughness (um)? 2.

Code Edge Length Width  Depth  F.R. S.R.
------------------------------------------------
 ZO  EX3   80.00   5.00   4.00  2.00  2.00
------------------------------------------------
Is that right (Y/N)? Y
```

- Information for flat feature 5:

```
What is the feature code ? OP

The feature selected is: Open pocket

Is that correct (Y/N)? Y
```

```
Edge code must be one of these :
      EX2, EX3, EY2 OR EY3
Input edge code : EX3

Input length (mm)? 30.

Input width (mm)? 20.

Input depth (mm)? 15.

Input face Roughness (um)? 2.

Input sides Roughness (um)? 2.

Input Radius (mm)? 12.5

Code Edge Length Width  Depth   F.R.  S.R.   RAD
-----------------------------------------------------
 ZO  EX3   30.00  20.00  15.00  2.00  2.00   12.50
-----------------------------------------------------
Is that right (Y/N)? Y
```

- A check on all flat features for ZO plane:

Flat features on ZO plane

NO.	FCD	Feature ID.	Length	Width	Depth	FR	SR	Edge	Radius
1	FT	Flat Face	80.00	100.00	5.00	4.00	0.00		0.00
2	SF	Step Face	60.00	60.00	15.00	3.00	3.00	EX3	0.00
3	ST	Slot	80.00	25.00	10.00	3.00	3.00	EX3	0.00
4	ST	Slot	80.00	5.00	4.00	2.00	2.00	EX3	0.00
5	OP	Open Pkt.	30.00	20.00	15.00	2.00	2.00	EX3	12.50

- Information for cylindrical features:

```
Any Cylindrical feature required on this plane (Y/N)? Y

How many Cylindrical features required on this plane? 3
```

- Information on cylindrical feature 1:

```
*************************************************************
                  Select the feature required
   Please enter the feature code as given in the list Below
*************************************************************
               CYLINDRICAL FEATURES GROUP
*************************************************************
   FEAT. IDEN.          CODE          FEAT. IDEN.        CODE
*************************************************************
   1- Simple hole       SMHL          2- Stepped hole    STHL
   3- Countersunk Hole CNSK           4- Thread          THRD
*************************************************************
```

```
What is the feature code ? CNSK

The feature selected is: Countersunk hole

Is that correct (Y/N)? Y

What is the hole centre X-coordinate ? 20.

What is the hole centre Y-coordinate ? 20.

What is the hole type:- 1) Through OR 2)Blind ? 2

Is it: 1) Flat ended  OR  2) Conical ended ? 1

What is the hole original condition:- 1)Solid or 2)Cored? 1

Input countersink angle (60 or 90)? 90

Input countersink depth (mm)? 7.5

Input hole diameter (mm)? 20.

Input hole depth (mm)? 10.

Input hole tolerance (mm)? .1

Input hole finishing (um)? 4.
```

Coordinates		H.Type	H.Org	End	HDia	HDep	HTl	HF	C/SAng	C/SDep
20.00	20.00	Blind	Solid	Flat	20.00	10.00	0.10	4.00	90	7.50

```
Is that right (Y/N)? Y
```

- Information on cylindrical feature 2:

```
What is the feature code ? STHL

The feature selected is: Stepped hole

Is that correct (Y/N)? Y

What is the hole centre X-coordinate ? 20.

What is the hole centre Y-coordinate ? 60.

What is the hole type:- 1) Through OR 2)Blind ? 2

Is it: 1) Flat ended  OR  2) Conical ended ? 2

What is the hole original condition:- 1)Solid or 2)Cored? 1

Input large hole diameter (mm)? 18.

Input large hole depth (mm)? 7.

Input large hole tolerance (mm)? .2

Input large hole roughness (um)? 3.

Input small hole diameter (mm)? 10.5

Input small hole depth (mm)? 20.

Input small hole tolerance (mm)? .2

Input small hole roughness (um)? 3.
```

Coordinates		H.Type	H.Org	End	SHDia	SHDep	SHTl	SHR	LHDia	LHDep	LHTl	LHR
20.00	60.00	Blind	Solid	Coni	10.50	20.00	0.20	3.00	18.00	7.00	0.20	3.00

Is that right (Y/N)? Y

- Information on cylindrical feature 3:

What is the feature code ? SMHL

The feature selected is: Simple hole

Is that correct (Y/N)? Y

What is the hole centre X-coordinate ? 82.5

What is the hole centre Y-coordinate ? 55.

What is the hole type:- 1) Through OR 2) Blind ? 1

What is the hole original condition:- 1)Solid OR 2)Cored? 1

What is the hole diameter in (mm)? 16.

What is the hole depth in (mm)? 30.

What is the hole tolerance in (mm)? .1

What is the hole roughness (um)? 6.

Coordinates		H.Type	H.Org	End	SHDia	SHDep	SHTl	SHR
82.50	55.00	Through	Solid		16.00	30.00	0.10	6.00

Is that right (Y/N) ? Y

- A check on all cylindrical features:

Would you like to check the cylindrical features data (Y/N)? Y

Cylindrical features on ZO plane

No	SCR	Feature Id	Coordinates		H.Type	H.Org	End	SHDia	SHDep	SHTl	SHA	LHDia	LHDep	LHTl	LHA
3	50	Simple hole	82.50	55.00	Through	Solid		16.00	30.00	0.10	6.0	0.00	0.00	0.00	00
2	40	Step hole	20.00	60.00	Blind	Solid	Coni	10.50	20.00	0.20	4.0	18.00	7.00	0.20	00
1	30	C/S Hole	20.00	20.00	Blind	Solid	Flat	20.00	10.00	0.10	4.0	0.00	7.50	0.00	90

- A check on all flat features:

Would you like to check all flat features on the component (Y/N)? Y

Flat features on XO plane

NO.	FCD	Feature ID.	Length	Width	Depth	FR	SR	Edge Radius
1	FT	Flat Face	50.00	80.00	4.00	4.00	0.00	0.00

Flat features on YO plane

NO.	FCD	Feature ID.	Length	Width	Depth	FR	SR	Edge Radius
1	FT	Flat Face	50.00	104.00	20.00	4.00	0.00	0.00

Flat features on ZO plane

NO.	FCD	Feature ID.	Length	Width	Depth	FR	SR	Edge	Radius
1	FT	Flat Face	80.00	100.00	5.00	4.00	0.00		0.00
2	SF	Step Face	60.00	60.00	15.00	3.00	3.00	EX3	0.00
3	ST	Slot	80.00	25.00	10.00	3.00	3.00	EX3	0.00
4	ST	Slot	80.00	5.00	4.00	2.00	2.00	EX3	0.00
5	OP	Open Pkt.	30.00	20.00	15.00	2.00	2.00	EX3	12.50

Would you like to check all cylindrical features in the component (Y/N)? N

Would you like to print out the procedure sheet (Y/N)? Y

Features will be planned for vertical milling machine only,
because horizontal milling machine cannot produce certain
features such as; Pockets (open, side or closed).

Would you like to keep the output data (Y/N)? Y

Would you like to keep it under the part number (Y/N)? Y

Would you want another GSCAPPP option (Y/N)? N

Once the user has inputted all the information required a request can be made for a print out of the process plan (procedure sheet), the system then automatically prints out a detailed plan containing 1. Header, 2. Cut-To-Length Section, 3. Milling Section and 4. Drilling Section. If any work holding devices are required, then the system indicates this at the end of the plan.

- Process plan output sheet:

P R O C E D U R E   S H E E T

Part Name: TCX-EXAMPLE1 | Drawing No: XXXXXX
Part No: EX00001 | Batch Type: CONTINUOUS
Part Material: MILD STEEL | Batch Size: 50
Part Size | Planner's Name: E.A.RUSTOM
L:W:H : 100.00 X 80.00 X 45.00 | Date: 27 JAN 92

S E C T I O N   O N E : C U T   T O   L E N G T H

OPERATION		MATERIAL		MACHINE		C. CONDITIONS		TIME
NO	DESC.	TYPE	CODE	NAME	CODE	LENGTH mm	SPEED m/min	Min.
1	SETUP	MS	MS15X15	METORA	UMB250	104.00		
2	SAWING	MS	MS15X15	METORA	UMB250	104.00		

S E C T I O N   T W O : M I L L I N G

OPERATION		MACHINE		CUTTING	TOOL			CUTTING	CONDITIONS						TOTAL
NO	DESC.	TYPE	CODE	ID	CODE	DIA mm	WID mm	PASS NO	CUT NO	WID mm	LEN mm	DEP mm	SPEED mm/mn	FEED mm/r	TIME min

YO plane features planning

1	SETUP														30.00

Flat surface Sequence

2	R Mill	V MILLER	VML	FCML	FC7	145.00	63.00	1	1	104.00	50.00	8.00	28	10	0.48
3	R Mill	V MILLER	VML	FCML	FC7	145.00	63.00	2	1	104.00	50.00	8.00	28	10	0.48
4	F Mill	V MILLER	VML	FCML	FC7	145.00	63.00	3	1	104.00	50.00	4.00	28	10	0.48

Total machining and non-machining time for this plane 31.44

XO plane features planning

1	SETUP														30.00

Flat surface Sequence

2	F Mill	V MILLER	VML	FCML	FC4	110.00	63.00	1	1	80.00	50.00	4.00	85	40	0.45

Total machining and non-machining time for this plane 30.45

ZO plane features planning

1	SETUP														30.00

Flat surface Sequence

2	F Mill	V MILLER	VML	FCML	FC7	145.00	63.00	1	1	100.00	80.00	5.00	28	10	0.67

Step face Sequence

3	R Mill	V MILLER	VML	ENDM	EN38	38.00	100.00	1	1	38.00	60.00	8.00	214	10	0.53
4	R Mill	V MILLER	VML	ENDM	EN38	38.00	100.00	1	2	22.00	60.00	8.00	214	10	0.42
5	R Mill	V MILLER	VML	ENDM	EN38	38.00	100.00	2	1	38.00	60.00	6.60	286	10	0.53
6	R Mill	V MILLER	VML	ENDM	EN38	38.00	100.00	2	2	22.00	60.00	6.60	286	10	0.42
7	F Mill	V MILLER	VML	ENDM	EN38	38.00	100.00	3	1	38.00	60.00	0.40	286	10	0.53
8	F Mill	V MILLER	VML	ENDM	EN38	38.00	100.00	3	2	22.00	60.00	0.40	286	10	0.42

Output Sheet Continued

Slot Sequence

9	TLCHG														1.50
10	R Mill	V MILLER	VML	SLOT	SL11	25.00	80.00	1	1	25.00	80.00	8.00	360	10	0.56
11	R Mill	V MILLER	VML	SLOT	SL11	25.00	80.00	2	1	25.00	80.00	1.60	475	10	0.56
12	F Mill	V MILLER	VML	SLOT	SL11	25.00	80.00	3	1	25.00	80.00	0.40	475	10	0.56

Slot Sequence

13	TLCHG														1.50
14	R Mill	V MILLER	VML	SLOT	SL4	4.00	12.00	1	1	4.00	80.00	3.60	1400	10	0.56
15	R Mill	V MILLER	VML	SLOT	SL4	4.00	12.00	1	2	1.00	80.00	3.60	1400	10	0.56
16	F Mill	V MILLER	VML	SLOT	SL4	4.00	12.00	2	1	4.00	80.00	0.40	1400	10	0.56
17	F Mill	V MILLER	VML	SLOT	SL4	4.00	12.00	2	2	1.00	80.00	0.40	1400	10	0.56

Open pocket Sequence

18	TLCHG														1.50
19	R Mill	V MILLER	VML	ENDM	EN25	25.00	100.00	1	1	20.00	30.00	8.00	360	10	0.22
20	R Mill	V MILLER	VML	ENDM	EN25	25.00	100.00	2	1	20.00	30.00	6.60	475	10	0.22
21	F Mill	V MILLER	VML	ENDM	EN25	25.00	100.00	3	1	20.00	30.00	0.40	475	10	0.22

Total machining and non-machining time for this plane 38.08

Total machining and non-machining time for flat features 68.53

S E C T I O N T H R E E : D R I L L I N G & B O R I N G O P E R A T I O N S

OPERATIONS		MACHINE		TOOLS			CUTTING CONDITIONS			M/CG
NO	DESCR.	NAME	CODE	IDENT	CODE	DIAM mm	LENG mm	FEED mm	SPEED rpm	TIME min

ZO plane features planning

1	SETUP **									90.00

Simple Hole Sequence

2	C.DRLG	R. Dril	RDL	C.DRILL	CDRL3	2.0	4.00	0.060	925	0.18
3	TLCHG									1.50
4	R.DRLG	R. Dril	RDL	T.DRILL	SHDL78	8.0	30.00	0.190	925	0.20
5	TLCHG									1.50
6	R.DRLG	R. Dril	RDL	T.DRILL	SHDL118	12.0	30.00	0.240	642	0.23
7	TLCHG									1.50
8	R.DRLG	R. Dril	RDL	T.DRILL	SHDL140	15.0	30.00	0.300	440	0.28
9	TLCHG									1.50
10	R.RMNG	R. Dril	RDL	REAMER	REAM26	15.5	30.00	0.600	229	0.27
11	TLCHG									1.50
12	F.RMNG	R. Dril	RDL	REAMER	REAM27	16.0	30.00	0.600	229	0.27

Output Sheet Continued

Stepped Hole Sequence

13	C.DRLG	R. Dril	RDL	C.DRILL	CDRL2	1.6	4.00	0.060	925	0.18
14	TLCHG									1.50
15	R.DRLG	R. Dril	RDL	T.DRILL	SHDL51	5.3	27.00	0.110	925	0.24
16	TLCHG									1.50
17	R.DRLG	R. Dril	RDL	T.DRILL	SHDL77	7.9	27.00	0.140	925	0.19
18	TLCHG									1.50
19	R.DRLG	R. Dril	RDL	T.DRILL	SHDL93	9.5	27.00	0.190	925	0.14
20	TLCHG									1.50
21	F.RMNG	R. Dril	RDL	REAMER	REAM15	10.0	27.00	0.380	440	0.15
22	TLCHG									1.50
23	F.RMNG	R. Dril	RDL	REAMER	REAM16	10.5	27.00	0.380	440	0.15
24	TLCHG									1.50
25	R.DRLG	R. Dril	RDL	CB.DRIL	CBOR10	10.4	27.00	0.190	925	0.15
26	TLCHG									1.50
27	R.DRLG	R. Dril	RDL	CB.DRIL	CBOR16	15.0	27.00	0.240	642	0.17
28	TLCHG									1.50
29	R.DRLG	R. Dril	RDL	CB.DRIL	CBOR18	17.2	27.00	0.300	440	0.21
30	TLCHG									1.50
31	F.RMNG	R. Dril	RDL	REAMER	REAM30	17.5	27.00	0.680	229	0.18
32	TLCHG									1.50
33	F.RMNG	R. Dril	RDL	REAMER	REAM31	18.0	27.00	0.680	229	0.18

Countersunck Hole Sequence

34	C.DRLG	R. Dril	RDL	C.DRILL	CDRL3	2.0	17.50	0.060	925	0.18
35	TLCHG									1.50
36	R.DRLG	R. Dril	RDL	T.DRILL	SHDL98	10.0	14.50	0.190	925	0.09
37	TLCHG									1.50
38	R.DRLG	R. Dril	RDL	T.DRILL	SHDL140	15.0	13.00	0.300	440	0.13
39	TLCHG									1.50
40	R.DRLG	R. Dril	RDL	T.DRILL	SHDL148	19.0	11.79	0.340	440	0.12
41	TLCHG									1.50
42	R.BORG	V-BORNG	BR1	B.BAR	B-BAR	19.5	11.64	0.340	480	0.11
43	TLCHG									1.50
44	F.BORG	V-BORNG	BR1	B.BAR	B-BAR	20.0	11.49	0.340	360	0.15
45	TLCHG									1.50
46	C.SNKG	R. Dril	RDL	CS.DRIL	CS603	31.5	8.49	0.340	440	0.14

Total machining and non-machining time for this plane 125.77

Total machining and non-machining time for cylindrical features 125.77

Total machining and non-machining time for the component 194.31

** SETUP time include both drilling and boring machines

Note: Drilling fixture is recommended.

6.3.2 Example 2: Partially Constant Cross-section Component (PCX-SEC)

Example 2 is of the Partially Constant Cross-section (PCX-SEC) type. The material of this component is carbon steel. The overall dimensions are 145.00 mm X 140.00 mm X 75.00 mm. It includes two plane surfaces that require machining. The first plane surface is the non-constant type and consist of: a stepped face, a slot, a side pocket, two plain blind holes (flat and conical ends), a through stepped hole and a through countersunk hole. The second plane is the constant type and contains: a stepped face and a slot as shown in **Figure 6.3**. The same procedure has been used to input the information as in the first example.

The best standard size selected for this example is shown in the screen display below:

```
          YOUR ORIGINAL DATA IS
-----------------------------------------
MATERIAL        LENGTH   WIDTH    DEPTH
-----------------------------------------
CARBON STEEL    145.00   140.00    75.00
-----------------------------------------

--------------------------------------------------
      THE POSSIBLE STANDARD SIZE(S)
--------------------------------------------------

USE CS SIZE : 150.00   150.00  CODE :CS15X15
CUT TO LENGTH :  153.00

--------------------------------------------------

==================================================
        THE BEST STANDARD SIZE IS
==================================================
USE CS SIZE : 150.00   150.00  CODE :CS15X15
CUT TO LENGTH :  153.00

      (Note: All dimensions in mm)
==================================================


 7.The standard size selected is larger by:
---------------------------------------------------------
      YD       YO       ZD       ZO       XD       XO
     5.00     5.00    37.50    37.50     4.00     4.00
---------------------------------------------------------
```

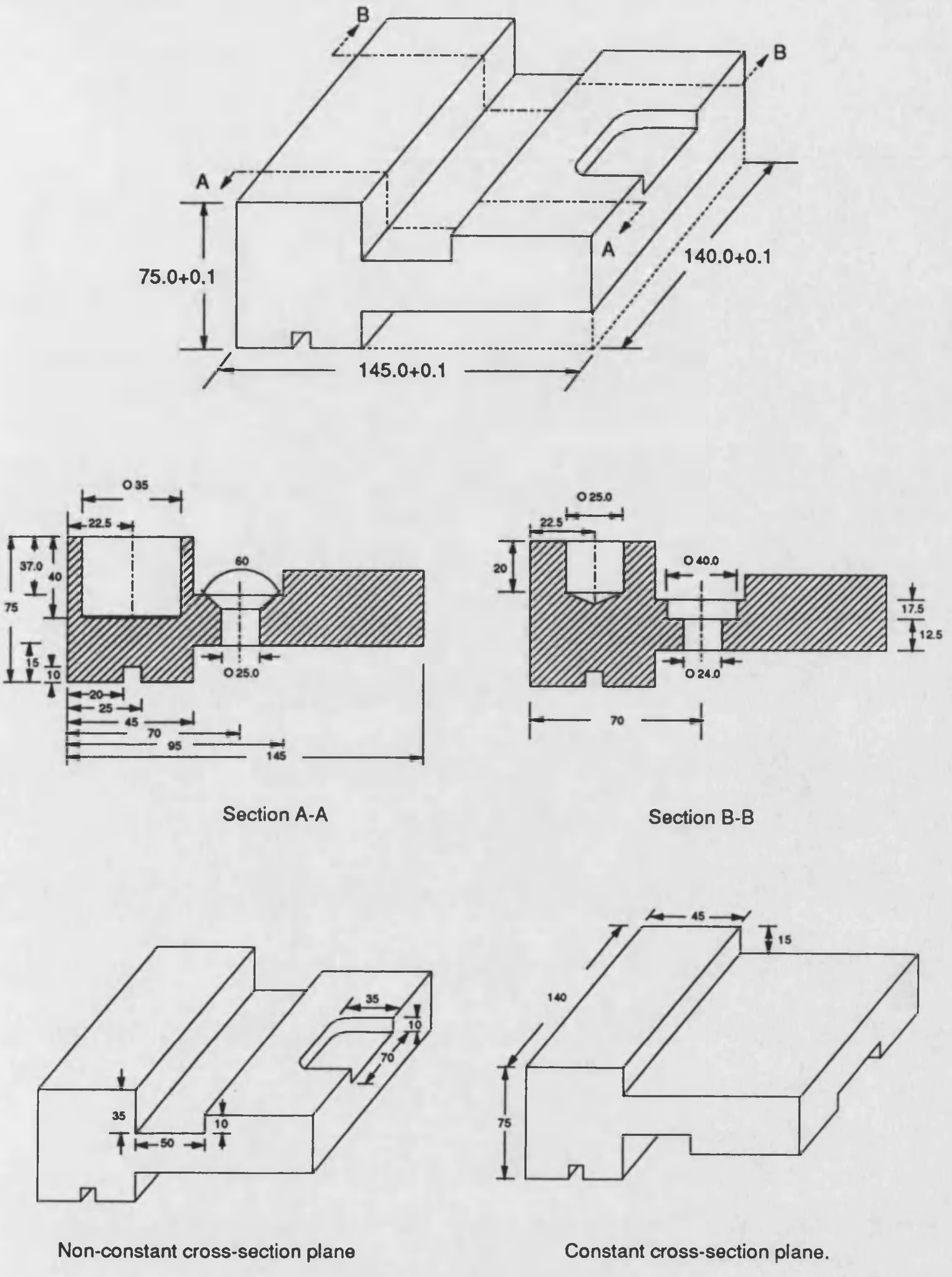


Figure 6.2: Example 2: PCX-SEC Component.

Figure 6.4 illustrates the component inside the selected raw material shape envelope and explains the sequences that have been used to decide which planes should be machined.

The difference in this example is that the user must define the component as non-constant. After editing the plane codes for the planes that require machining, the system asks whether the plane is a constant or a non-constant type. This enable the system to reorder the features on the non-constant plane according to the basic score and thereafter, the system displays these features with their basic scores. The following screen shows the planning order of the flat and cylindrical features on the component.

- Flat features on the component:

Flat features on XD plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR	SR
100	FT	Flat Face	150.00	145.00	5.00	3.00	0.00

Flat features on XO plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR	SR
100	FT	Flat Face	145.00	150.00	5.00	3.00	0.00

Flat features on YD plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR	SR
100	FT	Flat Face	150.00	150.00	4.00	3.00	0.00

Flat features on YO plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR
100	FT	Flat Face	150.00	150.00	4.00	3.00

Flat features on ZD plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR	SR	Edge
100	FT	Flat Face	140.00	150.00	37.00	3.00	0.00	
90	SF	Step Face	140.00	100.00	15.00	3.00	3.00	EX1

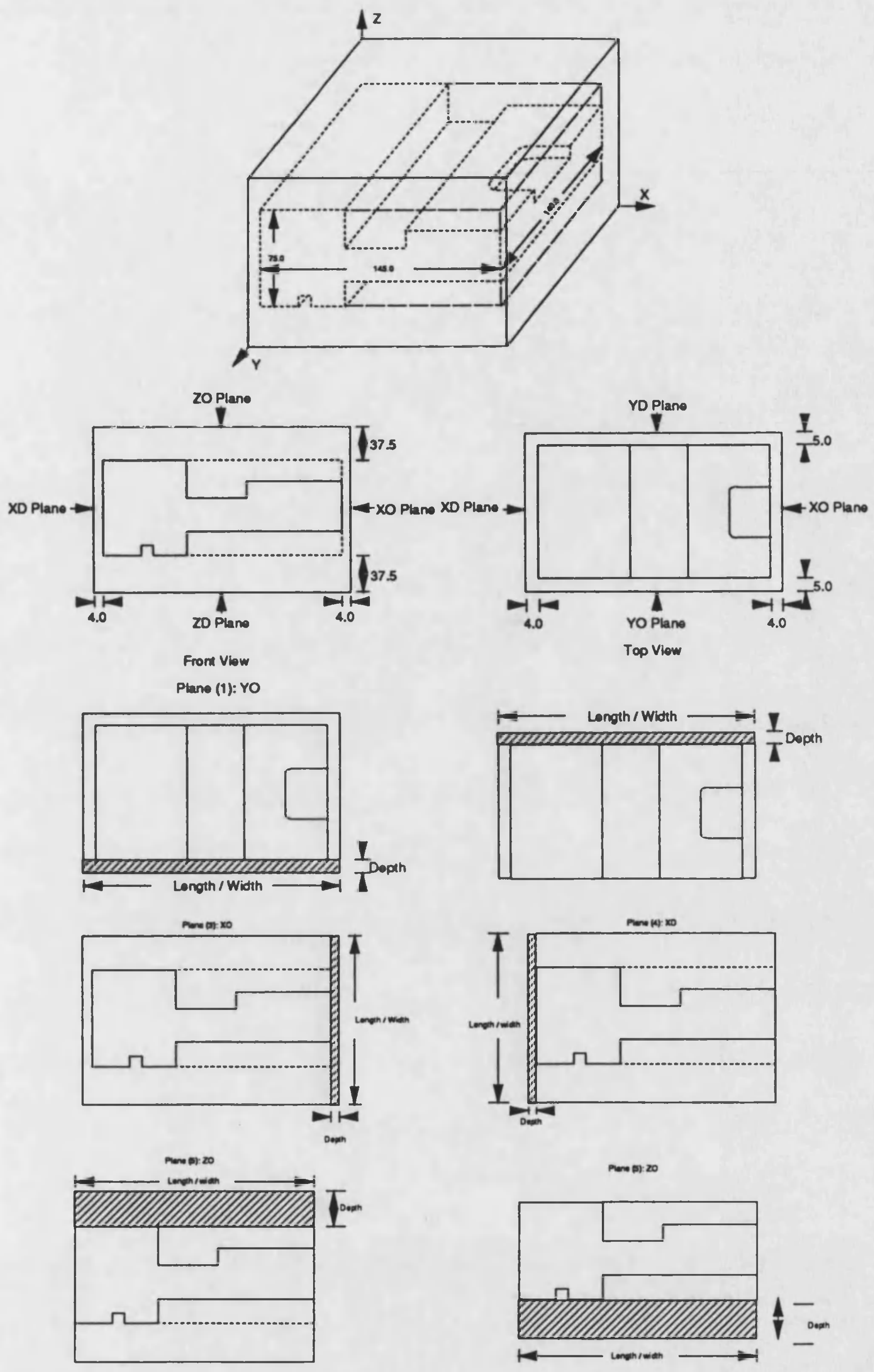


Figure 6.4: Planes Input Sequence for PCX-SEC Component.

Flat features on ZO plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR	SR	Edge	Radius
100	FT	Flat Face	140.00	145.00	37.00	3.00	0.00		0.00
90	SF	Step Face	140.00	100.00	25.00	3.00	3.00	EX3	0.00
80	SP	Side Pkt.	35.00	70.00	10.00	3.00	3.00	EY3	15.00
60	ST	Slot	140.00	50.00	10.00	3.00	3.00	EX3	0.00

- Cylindrical features on the component:

Cylindrical features on ZO plane

No	SCR	Feature Id	Coordinates		H.Type	H.Org	End	SHDia	SHDep	SHTl	SHR	LHDia	LHDep	LHTl	LHR
1	50	Simple hole	22.50	35.00	Blind	Solid	Flat	35.00	40.00	0.30	4.00	0.00	0.00	0.00	0.00
3	50	Simple hole	22.50	105.00	Blind	Solid	Coni	25.00	20.00	0.10	3.00	0.00	0.00	0.00	0.00
4	40	Step hole	70.00	105.00	Through	Solid		24.00	12.50	0.30	5.00	40.00	17.50	0.30	5.00
2	30	C/S Hole	70.00	35.00	Through	Solid		25.00	17.00	0.20	3.00	0.00	13.00	0.00	0.00

- Process plan output sheet:

P R O C E D U R E   S H E E T

Part Name: PCX-EXAMPLE2	Drawing No: XXXXXX
Part No: EX00002	Batch Type: DISCRETE
Part Material: CARBON STEEL	Batch Size: 100
Part Size	Planner's Name: E.A.RUSTOM
L:W:H : 145.00 X 140.00 X 75.00	Date: 27 JAN 92

S E C T I O N   O N E : C U T   T O   L E N G T H

OPERATION		MATERIAL		MACHINE		C. CONDITIONS		TIME
NO	DESC.	TYPE	CODE	NAME	CODE	LENGTH mm	SPEED m/min	Min.
1	SETUP	CS	CS15X15	METORA	UMB250	153.00		
2	SAWING	CS	CS15X15	METORA	UMB250	153.00		

S E C T I O N   T W O : M I L L I N G

OPERATION		M A C H I N E		CUTTING	TOOL			CUTTING	CONDITIONS						TOTAL
NO	DESC.	TYPE	CODE	ID	CODE	DIA mm	WID mm	PASS NO	CUT NO	WID mm	LEN mm	DEP mm	SPEED mm/mn	FEED mm/r	TIME min
	YO plane features planning														
1	SETUP														30.00
	Flat surface Sequence														
2	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	1	1	150.00	150.00	3.60	28	10	1.53
3	F Mill	V MILLER	VML	FCML	FC11	200.00	63.00	2	1	150.00	150.00	0.40	28	10	1.53
	Total machining and non-machining time for this plane														33.06
	YD plane features planning														
1	SETUP														30.00
	Flat surface Sequence														
2	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	1	1	150.00	150.00	3.60	28	10	1.53
3	F Mill	V MILLER	VML	FCML	FC11	200.00	63.00	2	1	150.00	150.00	0.40	28	10	1.53
	Total machining and non-machining time for this plane														33.06
	XO plane features planning														
1	SETUP														30.00
	Flat surface Sequence														
2	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	1	1	150.00	145.00	4.60	28	10	1.49
3	F Mill	V MILLER	VML	FCML	FC11	200.00	63.00	2	1	150.00	145.00	0.40	28	10	1.49
	Total machining and non-machining time for this plane														32.98

Output Sheet Continued

XD plane features planning

1	SETUP														30.00

Flat surface Sequence

2	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	1	1	145.00	150.00	4.60	28	10	1.51
3	F Mill	V MILLER	VML	FCML	FC11	200.00	63.00	2	1	145.00	150.00	0.40	28	10	1.51

Total machining and non-machining time for this plane 33.02

ZO plane features planning

1	SETUP														30.00

Flat surface Sequence

2	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	1	1	145.00	140.00	8.00	28	10	1.43
3	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	2	1	145.00	140.00	8.00	28	10	1.43
4	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	3	1	145.00	140.00	8.00	28	10	1.43
5	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	4	1	145.00	140.00	8.00	28	10	1.43
6	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	5	1	145.00	140.00	4.60	28	10	1.43
7	F Mill	V MILLER	VML	FCML	FC11	200.00	63.00	6	1	145.00	140.00	0.40	28	10	1.43

Step face Sequence

8	TLCHG														1.50
9	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	1	1	42.00	140.00	8.00	85	10	1.34
10	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	1	2	42.00	140.00	8.00	85	10	1.34
11	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	1	3	16.00	140.00	8.00	85	10	1.18
12	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	2	1	42.00	140.00	8.00	85	10	1.34
13	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	2	2	42.00	140.00	8.00	85	10	1.34
14	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	2	3	16.00	140.00	8.00	85	10	1.18
15	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	3	1	42.00	140.00	8.00	85	10	1.34
16	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	3	2	42.00	140.00	8.00	85	10	1.34
17	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	3	3	16.00	140.00	8.00	85	10	1.18
18	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	4	1	42.00	140.00	0.60	85	10	1.34
19	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	4	2	42.00	140.00	0.60	85	10	1.34
20	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	4	3	16.00	140.00	0.60	85	10	1.18
21	F Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	5	1	42.00	140.00	0.40	85	10	1.34
22	F Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	5	2	42.00	140.00	0.40	85	10	1.34
23	F Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	5	3	16.00	140.00	0.40	85	10	1.18

Side Pocket Sequence

24	TLCHG														1.50
25	R Mill	V MILLER	VML	ENDM	EN30	30.00	98.50	1	1	70.00	35.00	8.00	150	10	0.42
26	R Mill	V MILLER	VML	ENDM	EN30	30.00	98.50	2	1	70.00	35.00	1.60	150	10	0.42
27	F Mill	V MILLER	VML	ENDM	EN30	30.00	98.50	3	1	70.00	35.00	0.40	150	10	0.42

Slot Sequence

28	TLCHG														1.50
29	R Mill	V MILLER	VML	SLOT	SL20	50.00	100.00	1	1	50.00	140.00	8.00	85	10	1.29
30	R Mill	V MILLER	VML	SLOT	SL20	50.00	100.00	2	1	50.00	140.00	1.60	85	10	1.29
31	F Mill	V MILLER	VML	SLOT	SL20	50.00	100.00	3	1	50.00	140.00	0.40	85	10	1.29

Total machining and non-machining time for this plane 63.00

Output Sheet Continued

ZD plane features planning

1	SETUP														30.00
						Flat surface Sequence									
2	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	1	1	150.00	140.00	8.00	28	10	1.45
3	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	2	1	150.00	140.00	8.00	28	10	1.45
4	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	3	1	150.00	140.00	8.00	28	10	1.45
5	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	4	1	150.00	140.00	8.00	28	10	1.45
6	R Mill	V MILLER	VML	FCML	FC11	200.00	63.00	5	1	150.00	140.00	4.60	28	10	1.45
7	F Mill	V MILLER	VML	FCML	FC11	200.00	63.00	6	1	150.00	140.00	0.40	28	10	1.45
						Step face Sequence									
8	TLCHG														1.50
9	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	1	1	42.00	140.00	8.00	85	10	1.34
10	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	1	2	42.00	140.00	8.00	85	10	1.34
11	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	1	3	16.00	140.00	8.00	85	10	1.18
12	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	2	1	42.00	140.00	6.60	85	10	1.34
13	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	2	2	42.00	140.00	6.60	85	10	1.34
14	R Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	2	3	16.00	140.00	6.60	85	10	1.18
15	F Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	3	1	42.00	140.00	0.40	85	10	1.34
16	F Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	3	2	42.00	140.00	0.40	85	10	1.34
17	F Mill	V MILLER	VML	ENDM	EN42	42.00	101.50	3	3	16.00	140.00	0.40	85	10	1.18

Total machining and non-machining time for this plane 50.28

Total machining and non-machining time for flat features 212.34

S E C T I O N   T H R E E : D R I L L I N G & B O R I N G   O P E R A T I O N S

OPERATIONS		MACHINE		T O O L S			CUTTING CONDITIONS			M/CG
NO	DESCR.	NAME	CODE	IDENT	CODE	DIAM mm	LENG mm	FEED mm	ISPEED rpm	TIME min
				ZO plane features planning						
1	SETUP **									90.00
				Simple Hole Sequence						
2	C.DRLG	R. Dril	RDL	C.DRILL	CDRL4	2.5	4.00	0.060	925	0.18
3	TLCHG									1.50
4	R.DRLG	R. Dril	RDL	T.DRILL	SHDL86	8.8	37.37	0.190	440	0.54
5	TLCHG									1.50
6	R.DRLG	R. Dril	RDL	T.DRILL	SHDL145	17.5	34.74	0.340	229	0.61
7	TLCHG									1.50
8	R.DRLG	R. Dril	RDL	S.DRILL	SBDL147	27.0	32.12	0.430	159	0.72
9	TLCHG									1.50
10	R.DRLG	R. Dril	RDL	S.DRILL	SBDL153	33.0	30.09	0.480	110	0.97
11	TLCHG									1.50
12	R.BORG	V-BORNG	BR1	B.BAR	B-BAR	34.0	40.00	0.480	100	1.07
13	TLCHG									1.50
14	R.BORG	V-BORNG	BR1	B.BAR	B-BAR	34.5	40.00	0.480	100	1.08
15	TLCHG									1.50
16	F.BORG	V-BORNG	BR1	B.BAR	B-BAR	35.0	40.00	0.480	100	1.08

Output Sheet Continued

Simple Hole Sequence

17	C.DRLG	R. Dril	RDL	C.DRILL	CDRL4	2.5	4.00	0.060	925	0.18
18	TLCHG									1.50
19	R.DRLG	R. Dril	RDL	T.DRILL	SHDL123	12.5	20.00	0.240	319	0.34
20	TLCHG									1.50
21	R.DRLG	R. Dril	RDL	T.DRILL	SHDL148	19.0	20.00	0.340	229	0.36
22	TLCHG									1.50
23	R.DRLG	R. Dril	RDL	S.DRILL	SBDL144	24.0	20.00	0.380	159	0.48
24	TLCHG									1.50
25	R.RMNG	R. Dril	RDL	REAMER	REAM41	25.0	20.00	0.860	79	0.43
26	TLCHG									1.50
27	F.RMNG	R. Dril	RDL	REAMER	REAM41	25.0	20.00	0.860	79	0.43

Stepped Hole Sequence

28	C.DRLG	R. Dril	RDL	C.DRILL	CDRL3	2.0	4.00	0.060	925	0.18
29	TLCHG									1.50
30	R.DRLG	R. Dril	RDL	S.DRILL	SBDL144	24.0	30.00	0.380	159	0.36
31	TLCHG									1.50
32	R.DRLG	R. Dril	RDL	CB.DRIL	CBOR28	30.0	17.50	0.430	159	0.33
33	TLCHG									1.50
34	R.DRLG	R. Dril	RDL	CB.DRIL	CBOR31	33.0	17.50	0.480	110	0.45
35	TLCHG									1.50
36	R.DRLG	R. Dril	RDL	CB.DRIL	CBOR36	38.5	17.50	0.570	110	0.40
37	TLCHG									1.50
38	R.BORG	V-BORNG	BR1	B.BAR	B-BAR	39.0	17.50	0.570	100	0.44
39	TLCHG									1.50
40	F.BORG	V-BORNG	BR1	B.BAR	B-BAR	39.5	17.50	0.570	100	0.45
41	TLCHG									1.50
42	F.BORG	V-BORNG	BR1	B.BAR	B-BAR	40.0	17.50	0.570	100	0.45

Countersunck Hole Sequence

43	C.DRLG	R. Dril	RDL	C.DRILL	CDRL4	2.5	4.00	0.060	925	0.18
44	TLCHG									1.50
45	R.DRLG	R. Dril	RDL	T.DRILL	SHDL123	12.5	30.00	0.240	319	0.30
46	TLCHG									1.50
47	R.DRLG	R. Dril	RDL	T.DRILL	SHDL148	19.0	30.00	0.340	229	0.32
48	TLCHG									1.50
49	R.DRLG	R. Dril	RDL	S.DRILL	SBDL144	24.0	30.00	0.380	159	0.43
50	TLCHG									1.50
51	R.RMNG	R. Dril	RDL	REAMER	REAM41	24.5	30.00	0.860	79	0.38
52	TLCHG									1.50
53	F.RMNG	R. Dril	RDL	REAMER	REAM41	25.0	30.00	0.860	79	0.39
54	TLCHG									1.50
55	C.SNKG	R. Dril	RDL	CS.DRIL	CS604	40.0	30.00	0.860	79	0.43

Total machining and non-machining time for this plane	141.45
Total machining and non-machining time for cylindrical features	141.45
Total machining and non-machining time for the component	353.79

** SETUP time include both drilling and boring machines

6.3.3 Example 3: Non-Constant Cross-section Component (NCX-SEC)

Figure 6.5 shows example 3 which is of the non-constant cross-section (NCX-SEC) type. The overall dimensions are 120.0 mm X 120.0 mm X 120.0 mm and the material is aluminium. Three planes require machining: XD or XO, ZD and ZO. The selection between the XD and XO planes is left to the user. There is only one plain hole through the XD or XO planes. The ZO plane contains: an open pocket, a slot, a stepped face and a side pocket. The ZD plane contains: a stepped face and two slots.

The best standard raw material size found for this component is presented in the following screen display:

```
          YOUR ORIGINAL DATA IS
-----------------------------------------
 MATERIAL       LENGTH   WIDTH    DEPTH
-----------------------------------------
 ALUMINIUM      120.00   120.00   120.00
-----------------------------------------

--------------------------------------------------
      THE POSSIBLE STANDARD SIZE(S)
--------------------------------------------------

 USE AL SIZE : 150.00   150.00  CODE :AS15X15
 CUT TO LENGTH :  124.00

 USE AL SIZE : 125.00   125.00  CODE :AS12.5X12.5
 CUT TO LENGTH :  120.00

 USE AL SIZE : 125.00   125.00  CODE :AS12.5X12.5
 CUT TO LENGTH :  120.00

--------------------------------------------------

==================================================
        THE BEST STANDARD SIZE IS
==================================================
 USE AL SIZE : 125.00   125.00  CODE :AS12.5X12.5
 CUT TO LENGTH :  120.00

      (Note: All dimensions in mm)
==================================================


 17.The standard size selected is larger by:
--------------------------------------------------
         YD or YO      ZD     and     ZO
            5.00       2.50           2.50
--------------------------------------------------
```

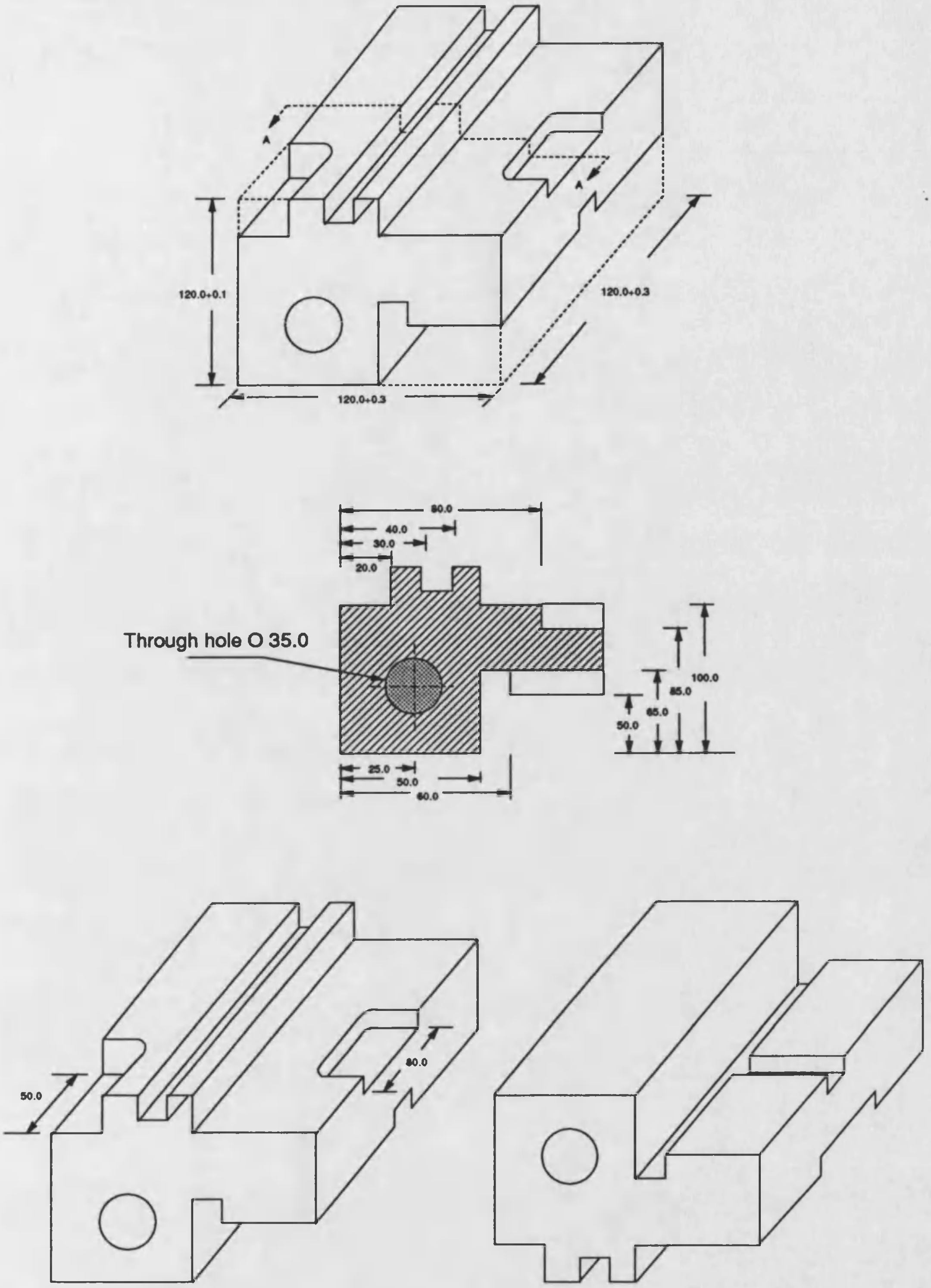


Figure 6.5: Example (3) NCX-SEC Component.

The following screen displays the flat and cylindrical features on the component.

- Flat features on the component:

Flat features on YO plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR
100	FT	Flat Face	120.00	120.00	10.00	4.00

Flat features on ZD plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR	SR	Edge
100	FT	Flat Face	120.00	120.00	5.00	3.00	0.00	
90	SF	Step Face	120.00	70.00	50.00	3.00	3.00	EX0
60	ST	Slot	120.00	20.00	15.00	4.00	4.00	EX0
60	ST	Slot	60.00	25.00	15.00	3.00	3.00	EY1

Flat features on ZO plane

Scr	FCD	Feature ID.	Length	Width	Depth	FR	SR	Edge	Radius
100	FT	Flat Face	120.00	120.00	5.00	3.00	0.00		0.00
90	SF	Step Face	120.00	70.00	20.00	3.00	3.00	EX3	0.00
80	SP	Side Pkt.	40.00	80.00	15.00	2.00	2.00	EY2	10.00
70	OP	Open Pkt.	20.00	50.00	30.00	3.00	3.00	EY3	15.00
60	ST	Slot	120.00	10.00	20.00	3.00	3.00	EX3	0.00

- Cylindrical features on the component:

Cylindrical features on YO plane

Coordinates		H.Type	H.Org	End	SHDia	SHDep	SHTl	SHR
25.00	45.00	Through	Solid		35.00	120.00	0.30	5.00

- Process plan output sheet:

P R O C E D U R E   S H E E T

Part Name: NCX-EXAMPLE3 | Drawing No: XXXXXX
Part No: EX00003 | Batch Type: DISCRETE
Part Material: ALUMINIUM | Batch Size: 35
Part Size | Planner's Name: E.A.RUSTOM
L:W:H : 120.00 X 120.00 X120.00 | Date: 27 JAN 92

S E C T I O N   O N E : C U T   T O   L E N G T H

OPERATION		MATERIAL		MACHINE		C. CONDITIONS		TIME
NO	DESC.	TYPE	CODE	NAME	CODE	LENGTH mm	SPEED m/min	Min.
1	SETUP	AL	AS15X15	METORA	UMB250	120.00		
2	SAWING	AL	AS15X15	METORA	UMB250	120.00		

S E C T I O N   T W O : M I L L I N G

OPERATION		M A C H I N E		CUTTING TOOL				CUTTING CONDITIONS							TOTAL
NO	DESC.	TYPE	CODE	ID	CODE	DIA mm	WID mm	PASS NO	CUT NO	WID mm	LEN mm	DEP mm	SPEED mm/mn	FEED mm/r	TIME min
					YO plane features planning										
1	SETUP														30.00
					Flat surface Sequence										
2	R Mill	V MILLER	VML	FCML	FC9	160.00	63.00	1	1	120.00	120.00	8.00	286	160	0.25
3	F Mill	V MILLER	VML	FCML	FC9	160.00	63.00	2	1	120.00	120.00	2.00	360	160	0.25
	Total machining and non-machining time for this plane														30.49
					ZO plane features planning										
1	SETUP														30.00
					Flat surface Sequence										
2	R Mill	V MILLER	VML	FCML	FC9	160.00	63.00	1	1	120.00	120.00	4.60	360	160	0.25
3	F Mill	V MILLER	VML	FCML	FC9	160.00	63.00	2	1	120.00	120.00	0.40	360	160	0.25
					Step face Sequence										
4	TLCHG														1.50
5	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	1	1	44.00	120.00	8.00	1010	10	0.24
6	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	1	2	26.00	120.00	8.00	1010	10	0.21
7	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	2	1	44.00	120.00	8.00	1010	10	0.24
8	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	2	2	26.00	120.00	8.00	1010	10	0.21
9	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	3	1	44.00	120.00	3.60	1301	10	0.24
10	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	3	2	26.00	120.00	3.60	1301	10	0.21
11	F Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	4	1	44.00	120.00	0.40	1301	10	0.24
12	F Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	4	2	26.00	120.00	0.40	1301	10	0.21

Output Sheet Continued

Side Pocket Sequence

13	TLCHG														1.50
14	R Mill	V MILLER	VML	ENDM	EN20	20.00	68.00	1	1	80.00	40.00	8.00	1400	10	0.08
15	R Mill	V MILLER	VML	ENDM	EN20	20.00	68.00	2	1	80.00	40.00	6.60	1400	10	0.08
16	F Mill	V MILLER	VML	ENDM	EN20	20.00	68.00	3	1	80.00	40.00	0.40	1400	10	0.08

Open pocket Sequence

17	TLCHG														1.50
18	R Mill	V MILLER	VML	ENDM	EN30	30.00	98.50	1	1	50.00	20.00	8.00	1400	10	0.05
19	R Mill	V MILLER	VML	ENDM	EN30	30.00	98.50	2	1	50.00	20.00	8.00	1400	10	0.05
20	R Mill	V MILLER	VML	ENDM	EN30	30.00	98.50	3	1	50.00	20.00	8.00	1400	10	0.05
21	R Mill	V MILLER	VML	ENDM	EN30	30.00	98.50	4	1	50.00	20.00	5.60	1400	10	0.05
22	F Mill	V MILLER	VML	ENDM	EN30	30.00	98.50	5	1	50.00	20.00	0.40	1400	10	0.05

Slot Sequence

23	TLCHG														1.50
24	R Mill	V MILLER	VML	SLOT	SL7	10.00	35.00	1	1	10.00	120.00	8.00	1400	10	0.22
25	R Mill	V MILLER	VML	SLOT	SL7	10.00	35.00	2	1	10.00	120.00	8.00	1400	10	0.22
26	R Mill	V MILLER	VML	SLOT	SL7	10.00	35.00	3	1	10.00	120.00	3.60	1400	10	0.22
27	F Mill	V MILLER	VML	SLOT	SL7	10.00	35.00	4	1	10.00	120.00	0.40	1400	10	0.22

Total machining and non-machining time for this plane 33.63

ZD plane features planning

1	SETUP														30.00

Flat surface Sequence

2	R Mill	V MILLER	VML	FCML	FC9	160.00	63.00	1	1	120.00	120.00	4.60	360	160	0.25
3	F Mill	V MILLER	VML	FCML	FC9	160.00	63.00	2	1	120.00	120.00	0.40	360	160	0.25

Step face Sequence

4	TLCHG														1.50
5	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	1	1	44.00	120.00	8.00	1010	10	0.24
6	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	1	2	26.00	120.00	8.00	1010	10	0.21
7	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	2	1	44.00	120.00	8.00	1010	10	0.24
8	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	2	2	26.00	120.00	8.00	1010	10	0.21
9	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	3	1	44.00	120.00	8.00	1010	10	0.24
10	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	3	2	26.00	120.00	8.00	1010	10	0.21
11	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	4	1	44.00	120.00	8.00	1010	10	0.24
12	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	4	2	26.00	120.00	8.00	1010	10	0.21
13	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	5	1	44.00	120.00	8.00	1010	10	0.24
14	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	5	2	26.00	120.00	8.00	1010	10	0.21
15	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	6	1	44.00	120.00	8.00	1010	10	0.24
16	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	6	2	26.00	120.00	8.00	1010	10	0.21
17	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	7	1	44.00	120.00	1.60	1301	10	0.24
18	R Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	7	2	26.00	120.00	1.60	1301	10	0.21
19	F Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	8	1	44.00	120.00	0.40	1301	10	0.24
20	F Mill	V MILLER	VML	ENDM	EN44	44.00	86.00	8	2	26.00	120.00	0.40	1301	10	0.21

Slot Sequence

21	TLCHG														1.50
22	R Mill	V MILLER	VML	SLOT	SL10	20.00	35.00	1	1	20.00	120.00	8.00	1400	10	0.21
23	F Mill	V MILLER	VML	SLOT	SL10	20.00	35.00	2	1	20.00	120.00	7.00	1400	10	0.21

Output Sheet Continued

Slot Sequence

24	TLCHG														1.50
25	R Mill	V MILLER	VML	SLOT	SL11	25.00	80.00	1	1	25.00	60.00	8.00	1400	10	0.11
26	R Mill	V MILLER	VML	SLOT	SL11	25.00	80.00	2	1	25.00	60.00	6.60	1400	10	0.11
27	F Mill	V MILLER	VML	SLOT	SL11	25.00	80.00	3	1	25.00	60.00	0.40	1400	10	0.11

Total machining and non-machining time for this plane 34.78

Total machining and non-machining time for flat features 68.41

S E C T I O N   T H R E E : D R I L L I N G & B O R I N G   O P E R A T I O N S

OPERATIONS		MACHINE		TOOLS			CUTTING CONDITIONS			M/CG
NO	DESCR.	NAME	CODE	IDENT	CODE	DIAM mm	LENG mm	FEED mm	SPEED rpm	TIME min

YO plane features planning

1	SETUP **									60.00

Simple Hole Sequence

2	C.DRLG	P DRILL	PL1	C.DRILL	CDRL4	2.5	4.00	0.060	966	0.17
3	TLCHG									1.50
4	R.DRLG	P DRILL	PL1	G.DRILL	DHDL7	16.0	120.00	0.190	966	0.68
5	TLCHG									1.50
6	R.DRLG	P DRILL	PL1	G.DRILL	DHDL9	18.0	120.00	0.340	966	0.39
7	TLCHG									1.50
8	R.DRLG	P DRILL	PL1	G.DRILL	DHDL24	33.0	120.00	0.480	447	0.61
9	TLCHG									1.50
10	R.BORG	V-BORNG	BR1	B.BAR	B-BAR	34.0	120.00	0.480	550	0.50
11	TLCHG									1.50
12	F.BORG	V-BORNG	BR1	B.BAR	B-BAR	35.0	120.00	0.480	480	0.57

Total machining and non-machining time for this plane 100.42

Total machining and non-machining time for cylindrical features 100.42

Total machining and non-machining time for the component 168.83

** SETUP time include both drilling and boring machines

6.4 Focus on BEPPS-GSCAPP Applications

The result of BEPPS-GSCAPPP applications have been favourably compared with process plans of various prismatic components provided by several batch manufacturing companies that use conventional machine tools. The three examples given in this chapter have been designed to cover all of the feature types, machine tools, cutting tools, logic rules, etc. contained in the system and the process plans produced lead to the following conclusions:

(1) The system has been shown to select the most economical standard size of raw material from stock. It also provide the user with access to the material files in order to update, add and/or delete any information from the material data base.

(2) It is important to follow the right procedure for inputting feature information because this can affect the result, particularly the machining time. For instance, in Example 2 the flat surface on both XD and XD have the same initial condition, but the input data is inputted differently, especially the length and width dimensions and this leads to a different machining time for both.

(3) The feature ordering techniques (Top-To Bottom and Scoring) have been shown to be effective and give good results.

(4) The system generates process plans according to the various input conditions, the component information, the raw materials, the machine capablities, the cutting tools available and the logic rules installed. The procedure sheet (process plans) details (i) general information (header), (ii) cut-to-length section (operation, material, machine, and cutting conditions), (iii) milling

section (operations, machine tools, cutting tools, cutting conditions and machining and non-machining time), (iv) drilling section (same as drilling section) and (v) holding device indication. Furthermore, the output sheet indicates the plane codes and the feature names and shows the machining time for each feature, for each plane, for the milling section, for the drilling section and finally for the whole component. The procedure sheet also shows the number of passes and number of cuts in addition to the feed and speed to be used.

(5) The system provides a help option on a separate screen which guides the user to input the data correctly and efficiently.

Chapter (7)

Conclusions and Recommendations for Further Work

7.1 Conclusions and Achievements

The developed system BEPPS-GSCAPPP is considered to meet the research objectives given in Chapter 1. The primary aim of developing an automated process planning system for prismatic parts is considered to have been achieved. However the scope of the system in its research form has been limited to parts produced on conventional machine tools that use a defined range of cutting tool types and sizes. Furthermore the parts that the system can effectively plan are limited to those containing features of a defined type.

In the earlier chapters of this thesis, the logic and the algorithms used in BEPPS-GSCAPPP have been discussed. Chapter 6 contains three examples of the type of part that the system can plan, together with the output of the planning activities. From these algorithms and results, it can be concluded that the three system stages used to achieved the basic goal have been effectively completed. These stages are: the *Interactive* stage, the *Automatic* stage and the *Output* stage. The interactive stage has been designed to collect all the information accurately for a component that is to be processed in the automatic and output stages. The automatic stage, which has been designed with a modular structure reorders and extracts the component and tooling information and then generates process plans using the logic and rules that have been installed in each module. When the automated planning has been completed, the output stage produces a detailed process plan for use on the shop floor.

The following achievements are considered to have been made.

(1) The efficiency of any generative process planning system relies on the knowledge base information and structure. The two types of knowledge *'factual'* and *'procedural'* that have been used by the system, increase its efficiency and performance. All of the external factual knowledge and information required for planning is extracted at the interactive stage. The information which comprises the internal factual knowledge has been elicited from various catalogues and stored in various files in the system's database. The general procedural knowledge and the procedural rules have been collected from industry and other relevant sources and have been installed within the system.

(2) The system, at present relies on the planner to input the component and other general information required for process planning via the interactive module. Thereafter, this information is kept in the input database file for future retrieval and/or modification. The input database file has been constructed to contain a separate information file for each component that can be identified by the component number. At the end of each section of the input stage, the system provides the planner with a list of the information that has been edited for a visual check and correction if required. The system uses this input methodology because there is no commercial CAD system as yet that can provide the total information required for process planning particularly for prismatic parts.

(3) In order to identify a feature on a prismatic component, two location elements should be specified: (i) the appropriate *plane surface* and (ii) the appropriate

edge. It is important to code the planes of a prismatic component as more than one plane is involved. This enables the planner to identify planes that require machining as well as assisting in the specification of feature location. It is also necessary to code edges in order to facilitate recognition of the cutting direction, especially for flat features. A simple coding system has been devised for both plane and edge coding. The six surface planes of the component have been classified into *Datum* and *Opposite* planes. They have been coded according to their corner coordinates with reference to the X, Y and Z axes. The edges also have been coded with reference to the X, Y and Z axes using an anti-clockwise direction technique. The codes of planes and edges at present need to be edited manually. No system has been found that claims to use automated plane and edge recognition algorithms.

(4) The system's raw material database file contains three types of standard raw material that are commonly used in batch manufacturing factories producing prismatic components. These materials are: *Mild steel*, *Carbon steel* and *Aluminium*. Existing commercial and research CAPP systems have not given significant attention to the selection of the appropriate raw material. An automatic raw material selection module has been constructed that can choose the most appropriate stock size available. The decision logic used takes into account the overall economics in coming to a decision. It is considered that economic advantages could also be gained by using this module as a stand-alone package in a design for manufacture environment.

(5) The simplified research system is based on 7 feature types that are divided into two main groups: the flat group which includes flat surface, stepped face, pocket and slot; and the cylindrical group which includes plain hole, stepped

hole and countersunk hole. Although feature-ordering is considered to be the most important element to automate in a generative CAPP system, it has not, as yet, been satisfactorily included in any current CAPP system. In BEPPS-GSCAPPP two techniques have been devised for feature ordering and successfully applied to components that can be described using the 7 feature types. The feature ordering technique *TOP-TO-BOT* is manual and based on the relative height of the flat features present on constant cross-section planes. The *SCORE* technique is automatic and relies on allocating a priority to individual features depending on their basic scores, and this is applied to non-constant cross-section planes. These techniques are considered to be unique and produce an effective feature order for process planning.

(6) The generation of a process plan also depends on the sequence of the individual processing operations that are needed to produce a finished component. Modules in the automatic stage have been designed to automatically generate several decisions using logic rules and machining information stored in the system's database. These decisions include the selection of the machine tool set, the selection of the appropriate cutting tools, the determination of the operation sequence, the selection of cutting conditions and the calculation of the machining and non-machining time. The only exception is that the sequence and operations for a threaded hole and a closed pocket are not as yet complete. The logic rules for surface and internal grinding have in general been identified but this process has not as yet been programmed into the system.

(7) The flexibility of a generative CAPP system is related to the structure of the database. The database should be organised in a way that can be easily

modified. The BEPPS-GSCAPPP database is constructed in such a way that enables easy access and data handling by user programs and easy modification by the planner, particularly in the case of the material, machine tool and cutting tool database files.

(8) The system automatically generates process plans for a defined range of components from the input information specified and then produces a detailed planning sheet for issue to the shop floor.

(9) The procedure sheet contains the following two sections: (1) The Header which includes a. General information, b. Component information and c. Production information. (2) The process plan which includes three subsections: a. Cut-to-length section, b. Milling section and c. Drilling and Boring section. Process plan information includes: operation type and sequence, machine type to be used, cutting tool type and size, cutting conditions (i.e. feed rate, speed and depth of cut) and total time calculation. If a workpiece holding device is required, the system indicates this at the end of the planning sheet.

(10) The system is capable of being extended to include logic for other component features and processes in order to increase its relevance to industry.

7.3 Recommendations for Future Work

The proposed system works, but now needs extending to increase its capabilities. Additional to that there is still some work to be done in order to fully automate the generative CAPP system. The following areas are recommended for future research:

(1) Raw Material Selection Module

The raw material selection module considers only three types of material and deals with standard forms and sizes and uses limited logic rules to select the appropriate size. In order to produce a more generally applicable system, three areas are recommended for expansion: (1) material type, (2) material form, and (3) cut to length operation. More standard material types used in manufacturing factories should be added, such as carbon steel of different grades, brass, etc. together with a greater range of sizes. Other forms of material such as castings and forgings should also be included. New logic and rules to select the appropriate raw material form will also be required. The logic rules for selecting the appropriate size needs to be extended to include other surface condition factors such as flatness. The cut-to-length operation can also be expanded to determine the cutting process, for example whether to use flame cutting or sawing using either sawing or milling machines. These recommendations would be required to complete a stand-alone package that many manufacturing factories could benefit from.

(2) Component Size and Features

The component size in BEPPS-GSCAPPP is restricted by the available machine tool set and the cutting tool capabilities to produce a full size range of component feature sizes. The features are also limited to 7 basic (flat and cylindrical) features with limited finishing conditions. To develop a more widely applicable system: (1) the component size has to be extended to include larger sizes, (2) the feature list has to be extended to include other flat and cylindrical types (3) feature specification should be extended to include other finishing requirements such as: flatness, roundness, true position parallelism, etc. and (4) the component type should be extended to include components with surfaces other than vertical and horizontal machined surfaces.

(3) Machine Tool Set and Cutting Tools Database Files

The machine tool and cutting database files at present include only a limited set of machines and cutting tools. In order to include larger components and increase feature types, additional types and sizes of machine tools and cutting tools are required that must be compatible with this expansion.

(4) Feature Ordering Techniques

Feature ordering in process planning is one of the important elements that requires great attention. The two feature-ordering techniques that have been constructed have basic rules that put features on a specified plane into an effective order. The concept of the *TOP-TO-BOT* technique is to plan flat features in the order as edited by the planner with reference to feature depth. This technique could be automated for each plane surface taking into account the plane surface code and edge codes. The order could be determined automatically by using feature depth and location as the main factors. The *SCORE* technique carried out automatically to re-order both flat and cylindrical features depending on the basic score given to each feature, as proposed in Chapter 5, could be modified to include logic conditions that refer to such factors as feature location, finishing conditions, machinability, etc. in order to increase the system efficiency.

(5) Cutting Condition Selection Module

The shop floor requires cutting conditions such as: feed rate, cutting speed and depth of cut. These factors are important as they affect the efficiency, productivity and hence, machining cost. However the factor, tool life, has not been included in the system, and its inclusion is needed to extend the potency of the system.

(6) Machining Operation Module

The machining operation module has been designed to determine the machining operations and their correct sequence to produce each feature. Machining operations as discussed in Chapter 5 are divided into *semi-finishing* and *finishing* operations. The finishing operations for flat features at present are carried out on standard machine tools where the finishing operations for cylindrical features are carried out on medium precision machine tools. For components requiring high finish requirements, precision machine tools should be included.

(7) Holding Device Module

Workpiece holding devices are also typically required by the floor shop during machining processes. There is a need for a compatible module that works together with other system modules in order to select or design the work holding device required. Such a module could significantly reduce the manufacturing lead time and improve quality.

(8) Decision Logic Handling

Decision logic in BEPPS-GSCAPPP has been developed within the system program modules. It is difficult for a person who is not familiar with Fortran programming to modify any logic or rules and this is one of the disadvantages of the Fortran language. Therefore, a method of updating the logic and rules is required that uses a conversation language which can enable this.

(9) Link with the BEPPS

As discussed earlier, BEPPS-GSCAPPP is part of the Bath Expert Process Planning System (BEPPS). Two other modules have been developed BEPPS-ROT and BEPPS-NC and for total integration of BEPPS, these three modules require a monitoring program to link them and control their functions.

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Appendix (A)

Preparation Instructions For Component

A.1 Introduction

This appendix is designed to help the BEPPS-GSCAPPP user to input component data in a proper way in order to achieve better and correct results. The following sections explain; (1) How the user should specify the overall dimensions of a component. (2) How the user should set the component dimensions in X, Y and Z coordinates. (3) How the user should code the component surface planes. (4) How the user should code the edges of the component shape envelope. and (5) How the user should determine the component type.

A.2 Overall Dimensions of a Component

To define a prismatic component, three main dimensions must be taken into account; *Length*, *Width* and *Depth*. These three dimensions are differentiated in the system according to their relative lengths in the shape envelope and are represented as follows;

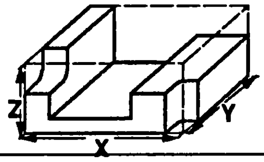
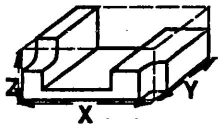
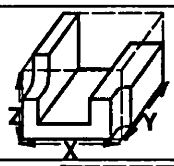
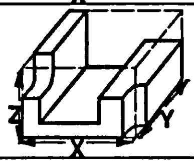
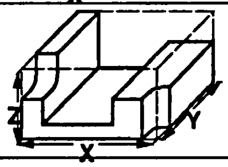
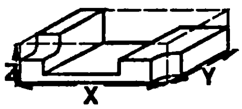
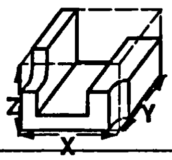
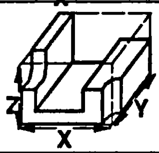
Length: *is represented by the higher dimension.*

Width : *is represented by the medium dimension.*

Depth : *is represented by the lower dimension.*

If two dimensions are *equal* and *higher* than the third, then; they should represent the **Length** and **Width**.

If two dimensions are *equal* and *lower* than the third, then; they should represent the **Width** and **Depth**, (See Figure A.1).

Value of			Component Overall Dimensions	Replace		
X	Y	Z		Length	Width	Depth
H	M	L	 X > Y > Z	X	Y	Z
H	H	L	 X = Y , Y > Z	X	Y	Z
L	H	H	 Y = Z , Z > X	Y	Z	X
H	L	H	 X = Z , Z > Y	X	Z	Y
H	L	M	 X > Z > Y	X	Z	Y
M	H	L	 Y > X > Z	Y	X	Z
M	L	H	 Z > X > Y	Z	X	Y
E	E	E	 X = Y = Z	X	Y	Z

E : Equal dimensions
H : Higher dimensions
M : Medium dimensions
L : Lower dimensions

Figure A.1: Component Overall Dimensions.

A.3 Component on X, Y and Z Wall Traps

Once the length, width and depth are determined, the user has to set the component dimensions with reference to X, Y and Z wall traps in order to prepare the component for the surface planes and edges coding. The system considers the following;

1- To set the component length along the X-axis.

2- To set the component width along the Y-axis.

3- To set the component depth along the Z-axis.

(See Figure A.2)

A.4 Plane Surface Coding

The six surface planes of the component shape envelope are named with reference to their locations on the three wall traps of X, Y and Z. The plane is called the x-plane if it is normal to the X-axis, y-plane if it is normal to Y-axis and z-plane if it is normal to Z-axis. Furthermore, these planes are divided into two types;

1- Datum Planes (3 planes coded as; XD, YD and ZD).

2- Opposite Planes (3 planes coded as; XO, YO and ZO).

XDatum plane is the plane at which the value of x on it's corner coordinates are equal to zero.

YDatum plane is the plane at which the value of y on it's corner coordinates are equal to zero.

ZDatum plane is the plane at which the value of y on it's corner coordinates are equal to zero.

XOpposite plane is the plane which is opposite to *XD*atum plane.

YOpposite plane is the plane which is opposite to *YD*atum plane.

ZOpposite plane is the plane which is opposite to *ZD*atum plane.

(See Figure A.3)

A.5 Edge Coding

Edge codes are derived according to their plane positions on the wall traps and original X, Y and Z axis positions.

Starting from the original *X-axis*, the edge code is **EX0**, moving in an anti-clockwise direction around the component shape envelope, the next five edge codes are **EX1**, **EX2**, **EX3**, **EX4** and **EX5** respectively.

Starting from the original *Y-axis*, the edge code is **EY0**, moving in an anti-clockwise direction around the component shape envelope, the next five edge codes are **EY1**, **EY2**, **EY3**, **EY4** and **EY5** respectively.

Starting from the original *Z-axis*, the edge code is **EZ0**, moving in an anti-clockwise direction around the component shape envelope, the next five edge codes are **EZ1**, **EZ2**, **EZ3**, **EZ4** and **EZ5** respectively.

At present, different levels on the same surface plane, use the same edge codes to represent it, (See Figure A.4).

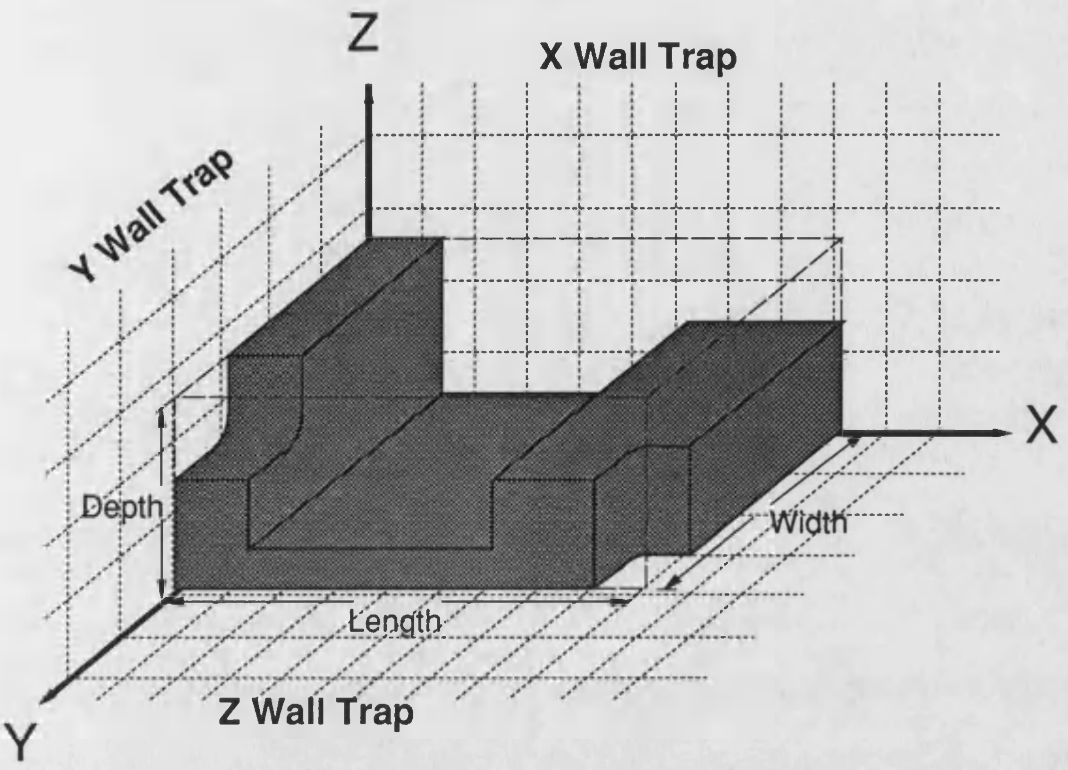
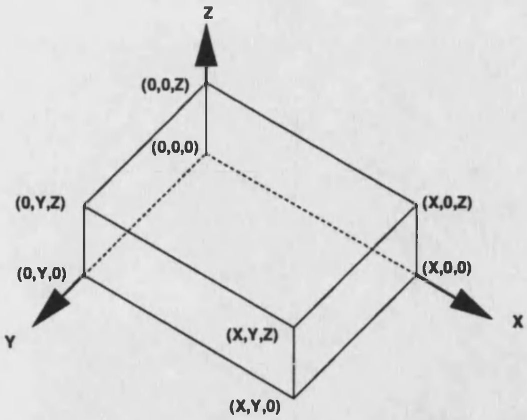
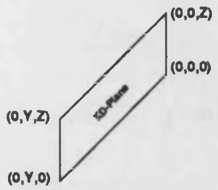
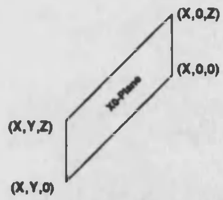
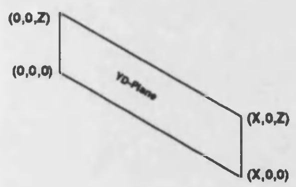


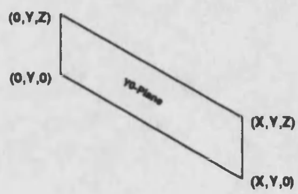
Figure A.2: The Component on X, Y and Z Wall Traps

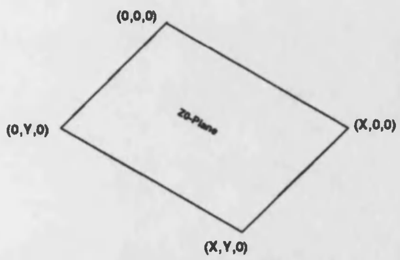


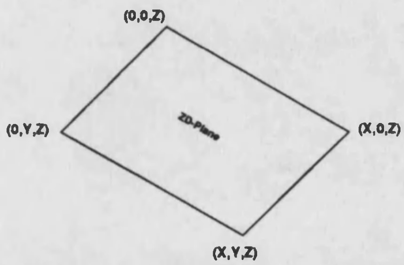
<table>
<tr><th>Datum Planes</th><th>Opposite Planes</th></tr>
<tr><td>

All values of x-coordinates are equal to zero</td><td>

All values of x-coordinates are equal to X</td></tr>
<tr><td>

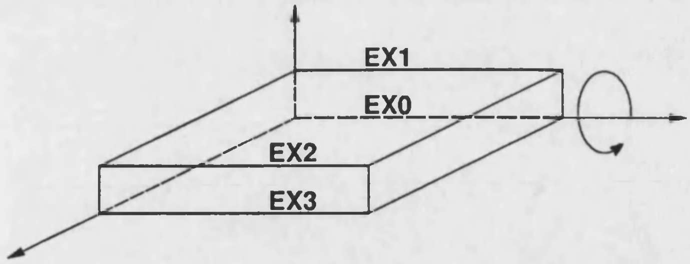
All values of y-coordinates are equal to zero</td><td>

All values of y-coordinates are equal to Y</td></tr>
<tr><td>

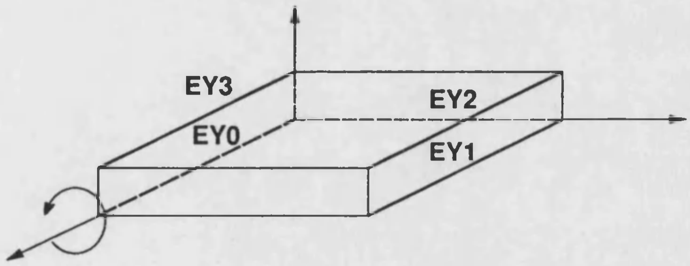
All values of z-coordinates are equal to zero</td><td>

All values of z-coordinates are equal to Z</td></tr>
</table>

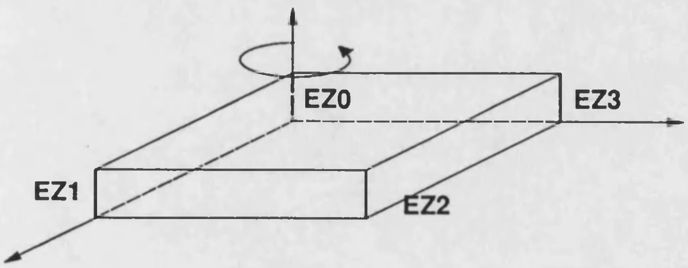
Figure A.3: Plane Coding



Starting from X-axis moving in an anti-clockwise direction



Starting from Y-axis moving in an anti-clockwise direction



Starting from Z-axis moving in an anti-clockwise direction

Fig. A-4: Edge Coding.

A.6 Component Type Determination

Components in the system are classified into;

1- Totally Constant Cross-Section TCX-SEC.

2- Partially Constant Cross-Section PCX-SEC.

3- Non-Constant Cross-Section NCX-SEC.

Elements to be considered before classification are;

a. Plane surfaces requiring machining.

b. Features from the flat group.

The main aim is to machine features on a plane in one set-up. Factors that control this classification are defined by the following attributes;

Attribute (1); *Feature profiles across the plane surface are constant.*

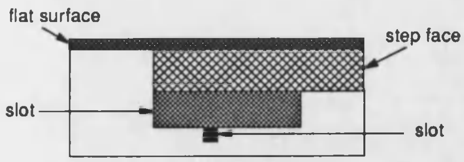
Attribute (2); *Machining direction of features on the plane surface are the same.*

According to the elements and attributes mentioned above, the following explains the difference between the three type of components.

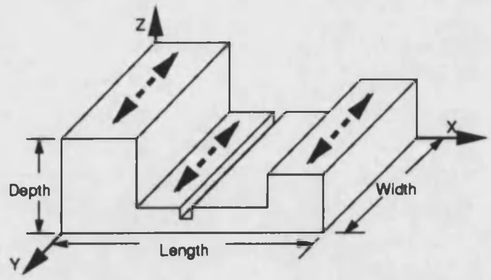
* The component is *TCX-SEC* if all plane surfaces requiring machining satisfy, at least, one of the above mentioned factors.
* The component is *PCX-SEC* if at least one plane surface requiring machining satisfies the above mentioned factors.
* The component is *NCX-SEC* if none of the plane surfaces requiring machining satisfy the above mentioned factors.

The computer program, at present, recognises a component as a constant (C) cross-section or as a non-constant (N) cross-section. The component which is of partially constant cross-section is considered initially to be of non-constant cross-section (N). Once the component type is inputted as non-constant (N), and after inputting the plane codes, the system asks whether the type of plane surface is constant or non-constant.

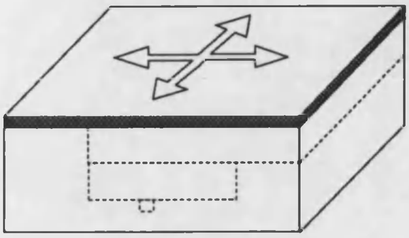
Figure A.5 (a) explains how to recognise a constant plane surface by examining the features profile across the plane and the cutting direction of the individual feature. **Figure A.5 (b)** shows a non-constant plane and the cutting direction of each feature.



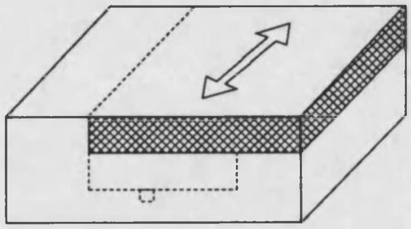
TCX-SEC Component Features



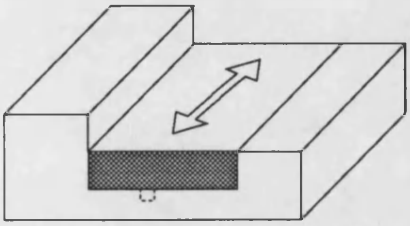
Plane surface with constant profile accross the width.



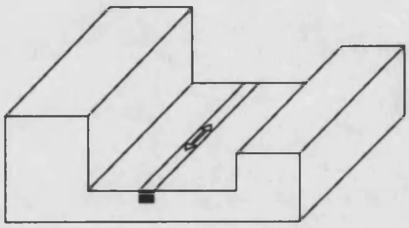
Cutting direction for flat surface using either horizontal or vertical machine



Cutting direction for step face using either horizontal or vertical machine



Cutting direction for slot using either horizontal or vertical machine

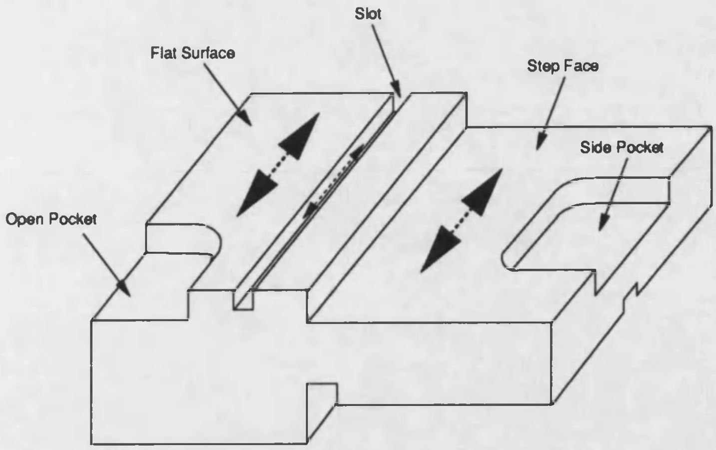


Cutting direction for slot using either horizontal or vertical machine

Plane ZO

Feature No.	1	2	3	4	Result
Constant Profile	✓	✓	✓	✓	Constant
Cutting Direction	↔↕	↕	↕	↕	Minimum one set-up

Figure A.5 (a): Checking Feature Profile and Cutting Direction on a TCX-SEC Component.



NCX-SEC Component

ZO Plane contains: (1) Flat Surface, (2) Slot, (3) Open Pocket, (4) Step Face and (5) Side Pocket.

Arrows indicates only a flat surface, a slot and a step face features have constant profile accross one dimension.

Plane ZO

Feature No.	1	2	3	4	5	Result
Constant Profile	✓	✓	✗	✓	✗	Non-constant
Cutting Direction	↔ ↕	↕	← ↑	↕	←	Minimum two set-ups

Figure A.5 (b): Checking Feature Profile and Cutting Direction on a NCX-SEC Component.

Appendix (B)

Instructions For Feature Data Input

B.1 Introduction

This appendix gives clear guidance on how the user should input feature data on each plane surface. But before that, the user has to consider the outcome of the material selection module and take into account the excess material that may be needed on top of the components overall shape envelope. Finally it explains the Top-To-Bottom technique used to input features in the correct order on the constant cross-section plane surface.

B.2 How to Deal With The Excess Material From The Raw Material Selection Module

At the input stage the user has to input the overall shape envelope of the component; in terms of the Length, Width and Depth together with their tolerances. Roughness requirements on all six surface planes are also required in order to select the appropriate size from stock. The tolerance on dimensions and the roughness of the plane surface are the two elements that influence the result of the *"appropriate size"*.

The system program is set to accept the *Basic TOLerance* **(BTOL)** on dimensions as **(0.25 mm)** to correspond to the raw material tolerance. In terms of roughness on planes, the system program is set to accept 4.00μm as the *Basic ROUghness* **(BROU)**.

512 rules are used to combine the tolerance and roughness in order to select the appropriate size. **Table B.1** illustrates some of these rules together with their results.

From these results, it is clear that excess metal of **(4.00 mm)** is added to the original dimensions if the tolerance on the length, for example, is less than the BTOL or either of XD or XO roughness is less than the BROU. The add metal procedure forms the new dimensions according to the original dimensions and plane requirements. The search for the exact or nearest size from stock then uses the new dimensions.

Once the appropriate size is selected, the system displays the chosen standard form and indicates the additional material with reference to the original dimensions. ***Note: The additional material should be considered as a feature (flat surface).***

In some cases, when the requirements of the datum and opposite planes are within the basic roughness and the tolerance is not, then the user may be required to choose between the datum and opposite planes. The following screen displays the outcome of example (1);

```
         Tolerence required on
   ------------------------------------------
       Length     Width     Depth
   ------------------------------------------
        0.200     0.200     0.200
   ------------------------------------------
         Roughness required on
------------------------------------------------
    XD       XO       YD       YO       ZD       ZO
------------------------------------------------
 4.000    4.000    4.000    4.000    4.000    4.000
------------------------------------------------

 Is that right (Y/N)? Y

        YOUR ORIGINAL DATA IS
-----------------------------------------
 MATERIAL        LENGTH   WIDTH    DEPTH
-----------------------------------------
 MILD STEEL      100.00    80.00    45.00
-----------------------------------------
```

Tolerance on						Roughness on												Additional Material on					
Length		Width		Depth		XD		XO		YD		YO		ZD		ZO		Length		Width		Depth	
GE. BT.	LT. BT.	GE. BT.	LT. BT.	GE. BT.	LT. BT.	GE. BR.	LT. BR.	GE. BR.	LT. BR.	GE. BR.	LT. BR.	GE. BR.	LT. BR.	GE. BR.	LT. BR.	GE. BR.	LT. BR.	XD	XO	YD	YO	ZD	ZO
*		*		*		*		*		*		*		*		*		N	N	N	N	N	N
*			*		*	*			*	*		*			*	*		N	A	A or A		A	N
	*		*	*			*	*		*			*		*	*		A	N	N	A	A	N
	*	*		*		*		*			*		*	*		*		A or A		A	A	N	N
*		*			*	*		*			*	*			*		*	N	N	A	N	A	A
	*		*		*		*		*	*			*	*		*		A	A	N	A	A or A	
*			*		*	*			*		*	*			*		*	N	A	A	N	A	A
*		*			*	*		*		*		*		*			*	N	N	N	N	N	A
	*		*	*		*		*		*		*			*	*		A or A		A or A		A	N
	*	*			*	*		*			*		*	*		*		A or A		A	A	A or A	
*		*			*		*	*		*		*			*		*	A	N	N	N	A	A
	*		*		*	*		*		*		*		*		*		A or A		A or A		A or A	
	*		*		*		*	*			*	*			*	*		A	N	A	N	A	N
*			*	*			*		*		*		*		*	*		A	A	A	A	A	N
	*	*		*			*		*	*			*		*		*	A	A	N	A	A	A

GE. : Greater or Equal to.
BT. : Basic Tolerance.
N : None.

LT. : Less Than.
BR. : Basic Roughness.
A : Additional Material.

A or A: Add material on either Datum or Opposite of length, width or depth.

Table B.1: Some Rules and Results of Additional Material.

```
----------------------------------------------------
       THE BEST STANDARD SIZE IS
----------------------------------------------------
 USE MS SIZE : 100.00     50.00  CODE :MF10X5
 CUT TO LENGTH :  104.00

      (Note: All dimensions in mm)
----------------------------------------------------


 13.The standard size selected is larger by:
-----------------------------------------------------------
           YD or YO  ,  ZD or ZO  and  XD or XO
            20.00        5.00         4.00
-----------------------------------------------------------
```

For example if the user has to choose between YD and YO, then the following weighted constraints have to be considered in order to choose one of the planes;

(1) Finishing requirement (15 points).

(2) Flat features (10 points).

(3) Cylindrical features (5 points).

Each of these constraints is given a value so that the user can calculate the weight of each plane and choose the one with highest value. If the weights for both planes are equal, then the user can choose either of them or choose the one with more features. The following examples explain how to choose the appropriate plane.

Example (1): If a choice is required between XD and XO and both have flat features, both have cylindrical features and XO requires lower finish than XD.

Weight: *XD weight = 15+10+5 = 30*

XO weight = 0+10+5 = 15

Example (2): If a choice is required between YD and YO and both have flat features, YO has cylindrical features and both require the same finish.

Weight: *YD weight = 15+10+0 = 25*

YO weight = 15+10+5 = 30

Example (3): If a choice is required between ZD and ZO, ZO has flat features only, ZD has cylindrical features only and both have the same finish.

Weight: *ZD weight = 15+00+5 = 20*

ZO weight = 15+10+0 = 25

B.3 Feature Data Input

It is important to input the feature data in a correct way in order to achieve an accurate result. Feature data input is summarised in **Figures B.1 (a)** and **B.3 (b)**. The only attention to be paid when inputting data for either flat surfaces or open pockets is that both have two possibilities of cutting direction.

If they are placed on a plane with a constant profile and hence, similar cutting directions, their *'length'* should be consider as in line with the cutting direction (see **Figure B.2**).

If they are placed on a plane with a non-constant profile, then the user has two alternatives;

Either

(1) To consider their lengths as in line with the cutting direction of the majority of features on that plane.

Or

(2) To consider the shortest dimensions as the length (note: depth dimension is not included here).

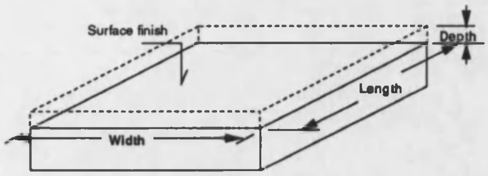
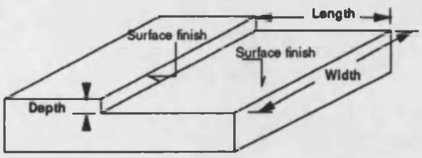
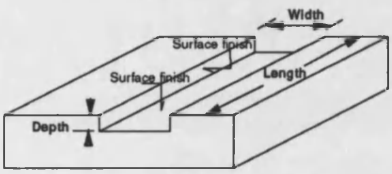
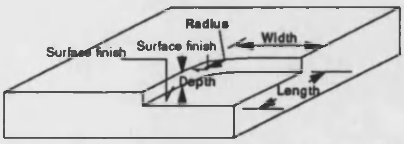
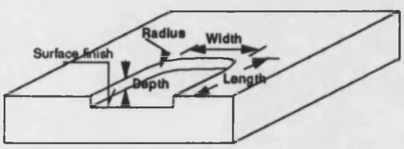
Flat Feature Group	Input Data	
 Flat Surface	Length. Width. Depth.	Face Roughness.
 **Step Face**	Length. Width. Depth.	Face Roughness. Side Roughness.
 **Slot**	Length. Width. Depth.	Face Roughness. Side Roughness.
 **Open Pocket**	Length. Width. Depth.	Face Roughness. Side Roughness. Radius.
 **Side Pocket**	Length. Width. Depth.	Face Roughness. Side Roughness. Radius.

Figure B.1 (a): Flat Feature Input Data.

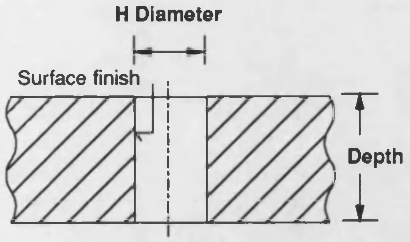
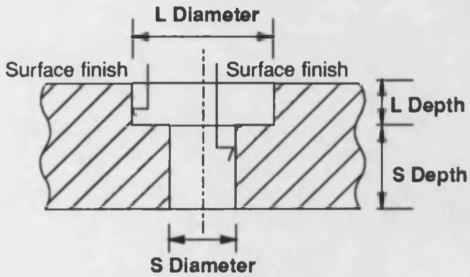
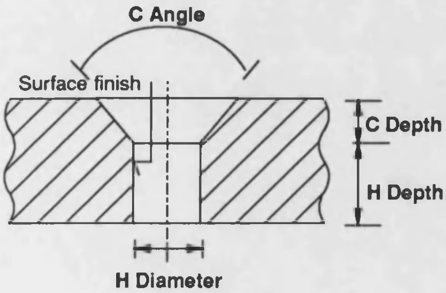
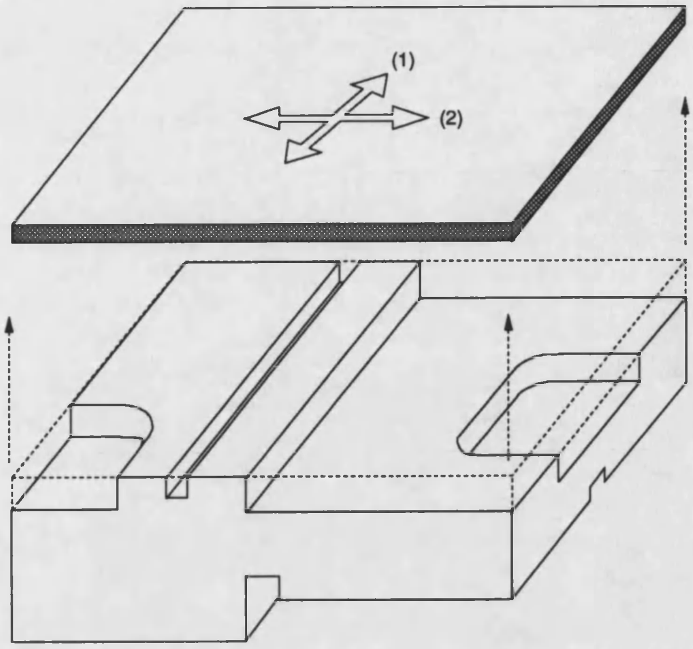
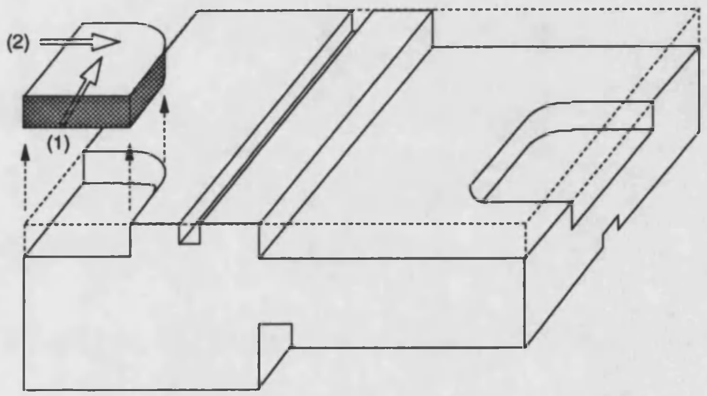
Cylindrical Feature Group	Input Data
 Plain Hole	Hole Diameter. Hole Depth. Hole Tolerence. Surface Finish.
 Step Hole	Large Hole Diameter. Large Hole Depth. Large Hole Tolerence. Large Hole Surface Finish. Small Hole Diameter. Small Hole Depth. Small Hole Tolerence. Small Hole Surface Finish.
 Countersunk Hole	Countersink Angle. Countersink Depth. Hole Diameter. Hole Depth. Hole Tolerence. Surface Finish.

Figure B.1 (b): Cylindrical Feature Input Data.



Flat Surface Cutting Directions



Open Pocket Cutting Directions

(1): Represents the cutting direction of majority of plane features.

(2): Represents the alternative cutting direction.

Figure B.2: Cutting Directions for Flat Surface and Open Pocket.

Table B.2: illustrates the typical roughness values obtainable by different processes and **Table B.3** shows the general tolerance for different processes that have been used by the system.

B.4 TOP-TO-BOT Technique for Feature Order

Once the plane surface is classified as a constant, the user is required to input features using the TOP-TO-BOT technique in order to achieve good results.

TOP-TO-BOT technique is applied for flat features that require machining on a constant cross-section plane surface. The concept of this technique is to put the feature on the high level prior to that one on the lower level. This enables the system to plan the machining sequences for the top feature prior to the bottom ones. The flat surface always should have priority over the other flat feature types. Some examples show how to apply this technique are illustrated in **Figure B.3.**

If more than one feature is on the same level, one the following considerations should be used;

(1) The user may input features according to the Scoring technique order.

(2) The user may input features using his/her own judgement.

The Scoring technique is applied for both flat and cylindrical features on non-constant cross-section planes. This technique is designed to reorder the plane features according to a basic score given to each feature. **Figure B.4** illustrates the hierachy of the feature order and their basic scores.

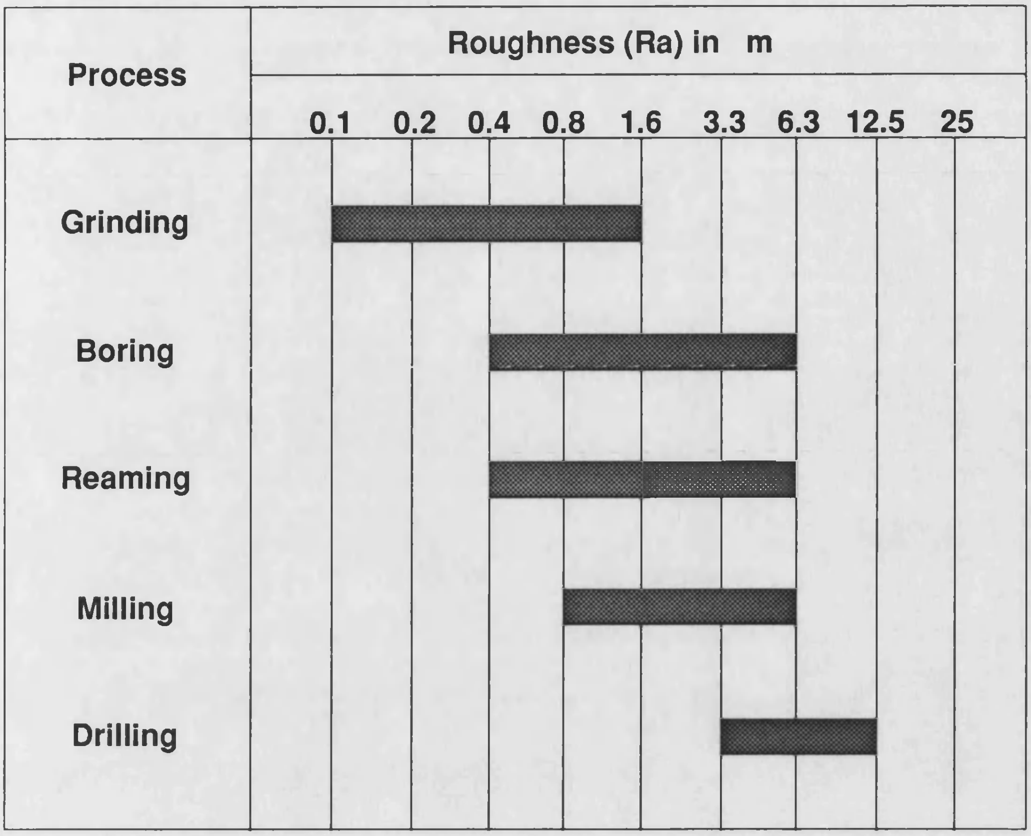


Table B.2: Typical roughness values obtained by different processes.

Process	Length or diameter of feature in mm							
	0-50	50-100	100-150	150-200	200-250	250-300	300-350	350-400
Grinding	0.0125	0.018	0.025	0.03	0.04	0.045	0.048	0.05
Finish Boring Reaming Milling	0.055	0.0625	0.07	0.075	0.0875	0.09	0.1	0.125
Drilling Rough Boring	0.325	0.375	0.420	0.45	0.48	0.52	0.55	0.58

Table B.3: General manufacturing tolerence (mm) for difference process.

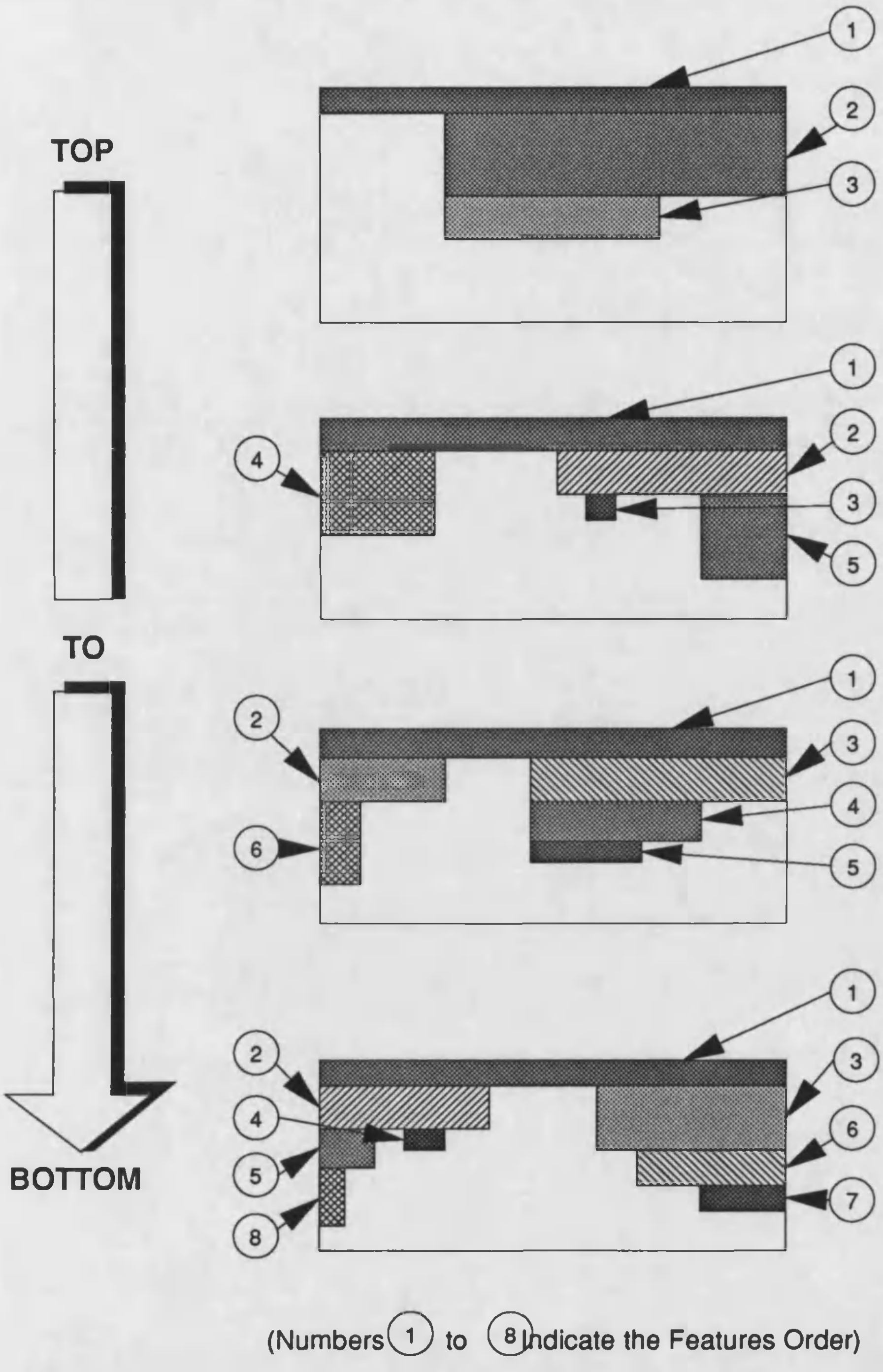


Figure B.3: Examples Show How to Use TOP-TO-BOTtom Technique.

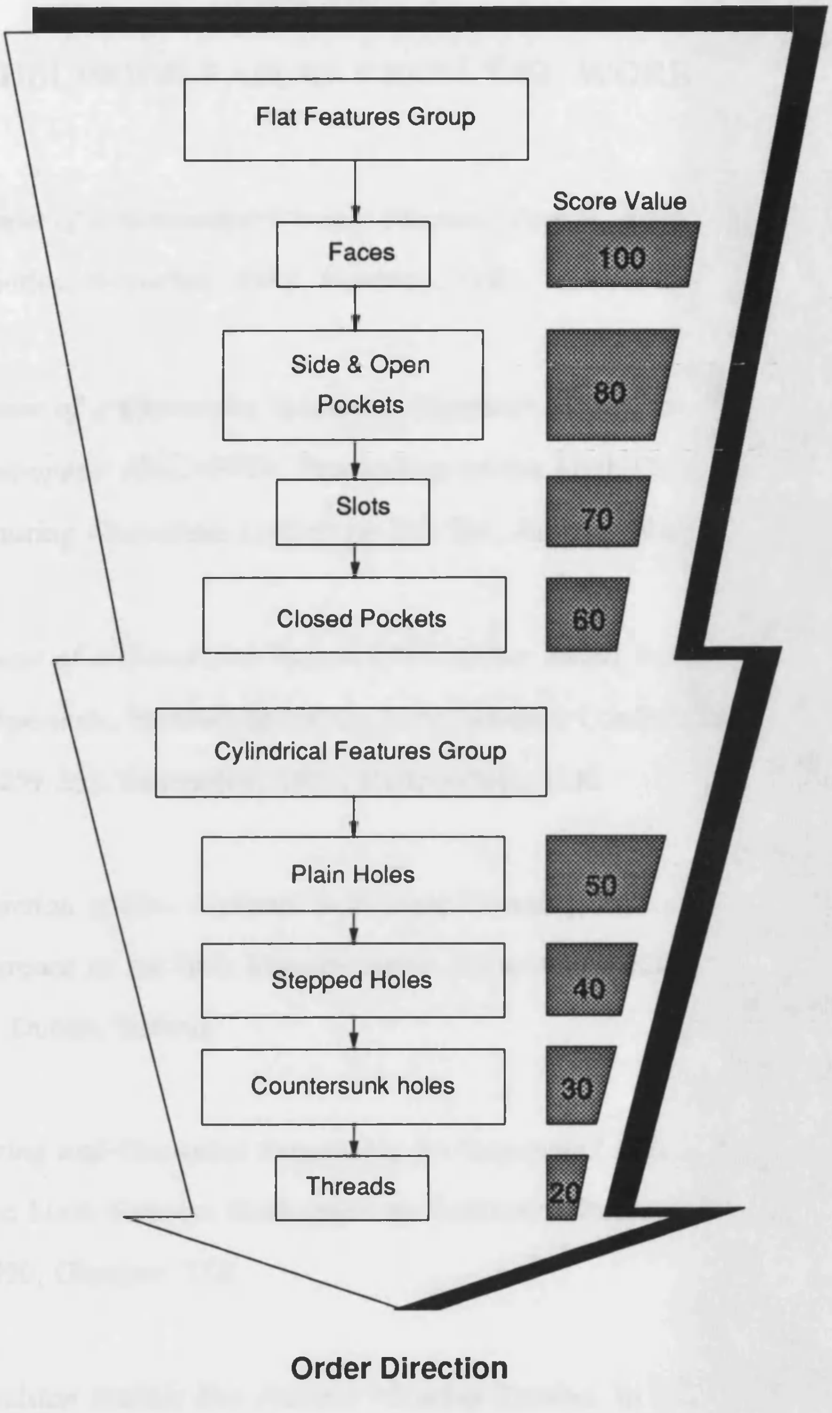


Figure B.4: BEPPS-GSCAPPP Feature Ordering Hierachy.

APPENDIX C

PUBLISHED PAPERS FROM THE WORK

1. *The Development of a Generative Process Planning System*, Advanced Manufacturing Seminar Series, November, 1988, Coventry, U.K.

2. *The Development of a Generative System of Computer Aided Process Planning for Prismatic Components (GSCAPPP)*, Proceedings of the Sixth Conference of the Irish Manufacturing Committee IMC-6, pp 192-201, August, 1989, Dublin, Ireland.

3. *The Development of a Generative System of Computer Aided Process Planning for Prismatic Components*, Proceedings of the Fifth National Conference on Production Research, pp 259-263, September, 1989, Huddersfield, U.K.

4. *Automatic Selection of Raw Material in Process Planning*, Proceedings of the Seventh Conference of the Irish Manufacturing Committee IMC-7, pp 70-77, August, 1990, Dublin, Ireland.

5. *Feature Ordering and Operation Sequencing for Automated Process Planning*, Proceedings of the Sixth National Conference on Production Research, pp 259-263, September, 1990, Glasgow, U.K.

6. *Automated Decision Making For Process Planning Systems*, to be published on the proceedings of the Joint International Conference FAIM 92, Flexible Automation and Information Management, June, 1992, Virginia, U.S.A.

ADVANCED MANUFACTURING SEMINAR SERIES

THE DEVELOPMENT OF A GENERATIVE PROCESS PLANNING SYSTEM

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ABSTRACT

BEPPS is a generative Computer Aided Process Planning (CAPP) system under preparation at the University of Bath. It has been designed with a modular structure that includes modules for conventional machines, NC machines, tooling and fixtures, cost estimating and links to both the CAD and Production Management systems. This paper describes the general strategy adopted and concentrates on the module for planning rotational components on conventional machine tools.

The turning module has an iteractive input routine designed to elicit non-expert information on component features, complexity and volume. After the input stage has been completed the computer system uses novel feature ordering logic based on rules gathered from industry to automatically choose the appropriate machines and tooling and generate the process plan.

1. INTRODUCTION

Process planning is the link between design and the production management systems that details the process route to be followed and the machines and equipment to be used.

In flow manufacturing, process planning typically involves the design of a special dedicated manufacturing system that is used to produce one component type for a multi-year run. The emphasis is on the machine and process choice and usually involves the consideration of the latest technologies. Process planning for flow systems tends to be a "once in a life time" exercise and has not as yet been targeted for computerisation.

In traditional batch and job manufacturing the manufacturing system is typically made up of groups of reasonably standard machines through which components are routed. Process planning involves detailing the most efficient route through the machines that are available and the routes specified will thus vary from company to company. It is in this type of planning environment that Automated Process Planning or CAPP has made an industrial impact in recent years. It is not unusual for a batch working company to plan several hundred new or modified components per month. A change from manual planning to CAPP could well provide for such a company benefits in the following areas.

Increased planning productivity - 600%
Reduced lead times
Improved documentation - better consistency legibility and less error
More consistent planning

Many batch manufacturing companies have invested in CNC, FMS and CIMS (Computer Integrated Manufacturing System) type installations. However the process routes followed through such systems still contain many non-automated operations such as "cut bar to length", "face and centre", "heat treat", "grind" and "deburr" etc. In these companies CAPP systems have also been used to great advantage and appear to give greater benefits than direct CADCAM links. In fact it has been claimed that for CIMS, CAPP facilitates the efficient transfer of information from CAD through to CAPM (Computer Aided Production Management) and provides the basis for a truly integrated system.

Several CAPP systems are on the market, for example:-

C-Plan
Locam
Supercapes
Multi-CAPP
Cequel
Sofie 2
These fall into three main types:

(a) Constructive
The Plan is formulated by the planning engineer, from a library of standard phrases. Once a machine type has been identified the system will present a list of available machines to the planner to choose from. When the choice of machine and tooling has been made typically such systems will automatically choose appropriate speeds and feeds and then calculate the operation times.

(b) Variant

This approach is particularly applicable for component populations that can be readily grouped into families of similar shaped components and normally a shape code is used to assist in the classification process. A process plan that covers all of the components in a family will be produced and any new component or family variant will be planned by modifying the family plan. If a component family can be parametised a manufacturing file can be produced during CAD and then used to generate process plans automatically.

(c) Generative

In theory a system could be developed that, given the component features to be machined and a set of expert rules relating to process and operation choice, could generate process plans completely automatically for any component.

In general only the first two types of CAPP system have been developed sufficiently for industrial use. However if true generative planning is made to work efficiently then process plans could be produced on demand from a MRP type system with due regard to short term machine availability. This would allow process planning to minimise the total throughput time for a component and not as is typical the floor to floor time.

2. GENERAL STRUCTURE OF BEPPS

This paper describes BEPPS a generative CAPP system that is in preparation at the University of Bath.

Figure 1 shows the areas that are currently being developed to provide a complete process planning system.

It is modular in construction with each module being capable of running on a stand alone basis.

The three planning modules all use a similar structure as shown in Figure 2. Information about the component features to be machined together with more general data is inputted into a Component Data File. This file, which can be constructed manually or eventually direct from CAD, is used as the input to the automated process planning routines. Expert rules are used for process planning that have been elicited from industry. These order the sequence in which features are machined and select the machines equipment and conditions to produce them.

As an example of the approach adopted the module for turning components on conventional machine tools[3] has been chosen to be described in greater detail.

3. BEPPS - TURNING PROGRAM STRUCTURE

All CAPP systems require data files to be constructed on for example the available machines, materials, tooling, processes and costs. Information is also required in terms of machine and tooling capabilities, tool life and other process boundary information. In the turning module these are based on a machine shop containing conventional turning machines using carbide tooling that produce components from bar stock. With the parameters of this machine shop embedded in the computer data base any turned component within its range can be process planned automatically by following a set procedure.

Firstly information describing the component is required from the planner after which the computer generates the plan and issues the documentation. The structure of BEPPS turning is given in Figure 3.

4. COMPONENT INFORMATION INPUT

4.1. General

Given a component drawing a planner is required to answer a variety of general questions before inputting component feature information.

The general input requirements include:

(a) Maximum diameter and length
(b) Output volume or batch size
(c) Repeat or one off batch
(d) Best orientation (which end is to be held)
(e) If axial holes are present and which way they increase in diameter
(f) If non axial holes are present
(g) If certain grooves are present.

From this initial input the computer codes the component using up to 5 digits. The code does not define shape explicitly but is used within the computer to make certain decisions.

For example at this point the computer system chooses:

(i) the most appropriate machine tool
(ii) the best method of work holding (bar feed, chuck, between centres)

(iii) the most appropriate non-machining operations.

4.2. Feature Identification

The philosophy adopted is to split the component into the individual features that require machining (taper, chamfer, thread etc). Turned components are made up of a limited number of features and in BEPPS, 14 have been identified, from which virtually any turned component can be constructed. Each feature type is given a specific alpha-numeric code.

Starting from the tailstock end of the component, the planner is required to input parametric information about each external feature in turn and then, moving back to the exposed end, about each internal feature.

This information is recorded in the component data file, which will also be able to accept the co-ordinate information direct from CAD. But as CAD information does not typically include, tolerances or surface roughness etc., the data file is constructed by the planner. A reference manual is available to ensure consistency of surface interpretation.

5. AUTOMATED PROCESS PLANNING

The component data file is used for both automated process planning and to produce a graphical display of the component.

5.1 Graphical Display

Other generative systems that have been put forward, APPAS[1], GENPLAN[1], AUTAP[2] and CPPP[1] although using surface codes to describe components have had difficulty in producing a screen drawing from the input information. In BEPPS the component data file can be used directly to give a screen display of the component on which each feature inputted is labelled. This serves as an important visual check of the data files validity.

5.2 Feature Ordering

The sequence in which features are machined or combined for machining is an important consideration. In variant systems the sequence is contained within the standard plans but in generative systems expert geometric precedence rules must be incorporated. In the majority of generative systems described in the literature feature ordering has been achieved interactively by the user or automatically by using very simple conditions. Geometric precedence rules can be grouped into 3 types.

1. Two surfaces are related such that access to the second is gained only after machining the first, e.g. a groove on a turned surface. Here it is evident on technological grounds, that surface one should precede two.

2. Two surfaces are related but neither impose a strict technological precedence on the other. Here expert rules form the basis of the feature ordering in BEPPS.

3. Cases where components require transfer to another machine. Expert rules are again being formulated to decide for example whether a keyway should precede a flange hole[4]

The feature ordering module for BEPPS is in preparation and different approaches are being evaluated. As expert rules vary it is possible to embed common rules and allow companies to add the remainder to suit their manufacturing systems. Alternatively it is possible to build in alternative rules with a view to generating competitive plans. At present in BEPPS feature ordering is carried out partially interactively at the input stage and partially automatically during process planning.

5.3 Knowledge Elicitations and Process Selection

BEPPS is a rule based system that utilises a data base of factual knowledge and procedural rules. The factual knowledge includes process and tooling capability data. Procedural rules have been elicited from a variety of sources. In certain cases adequate information is available in reference books but extensive use has also been made by eliciting expert knowledge from industry. This has been achieved by production engineers completing a range of specimen plans and also by interviews and questionnaires. To date a set of 300 plus rules have been archived. The rules interact with the factual knowledge to provide planning logic for each feature from which the machining operations are detailed. The rules have been coded in Fortran 77, mainly in the form of IF - THEN statements. The rules and process boundary tables have been structured such that modification of the factual knowledge can be achieved without the need for restructuring.

6. CONCLUSION

A generative process planning system BEPPS is in preparation. It consists of several interrelated modules of which the turning module for planning rotational components on conventional machine tools is the most advanced. This module incorporates novel approaches to component classification, feature identification and feature ordering through a rule based system that uses factual and procedural knowledge. Although it has not been used commercially it is felt that it has considerable industrial potential particularly when the NC and prismatic modules are added.

7. REFERENCES

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CAPP OVERVIEW

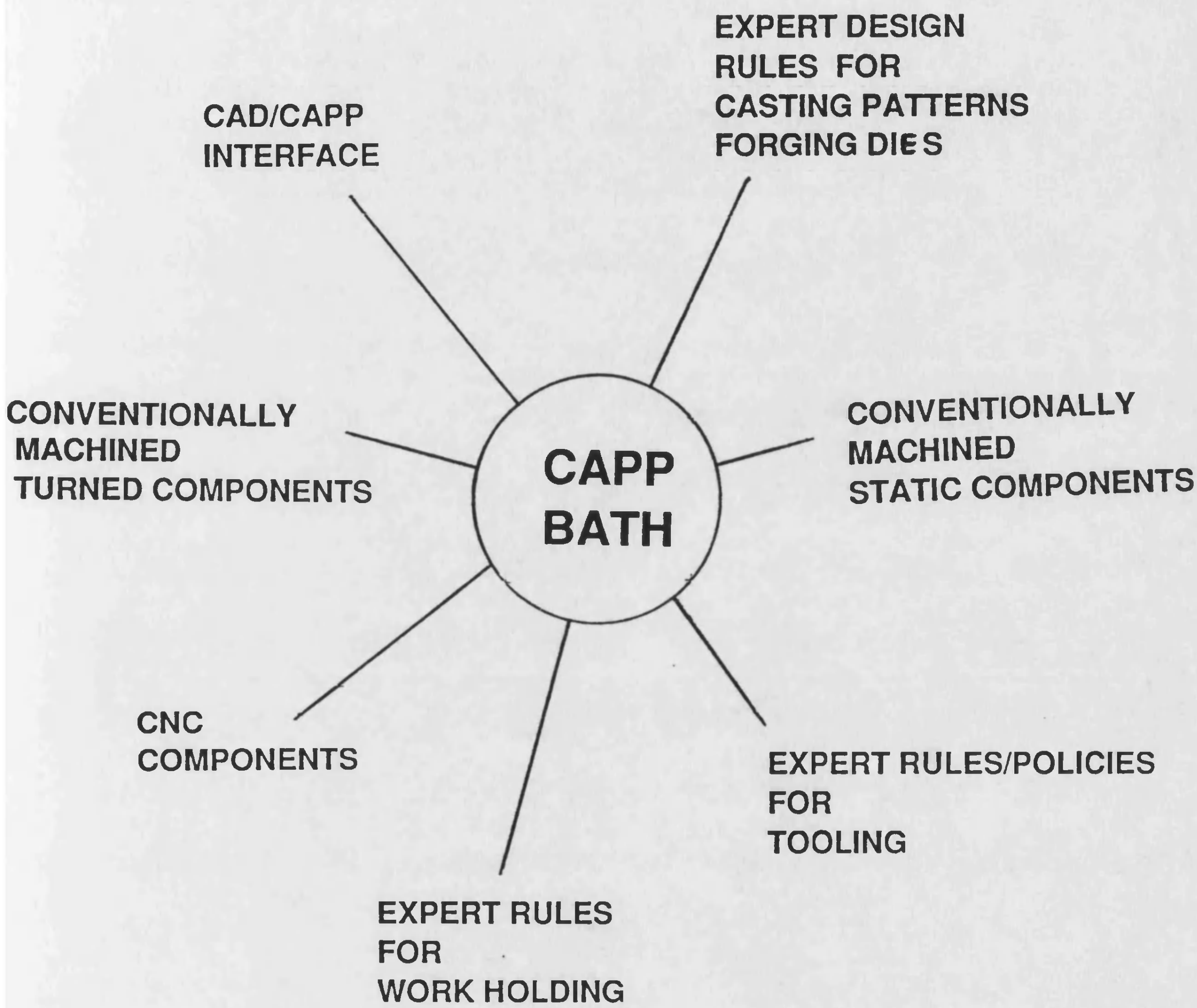

Figure 1. OVERVIEW OF CAPP RESEARCH AT BATH

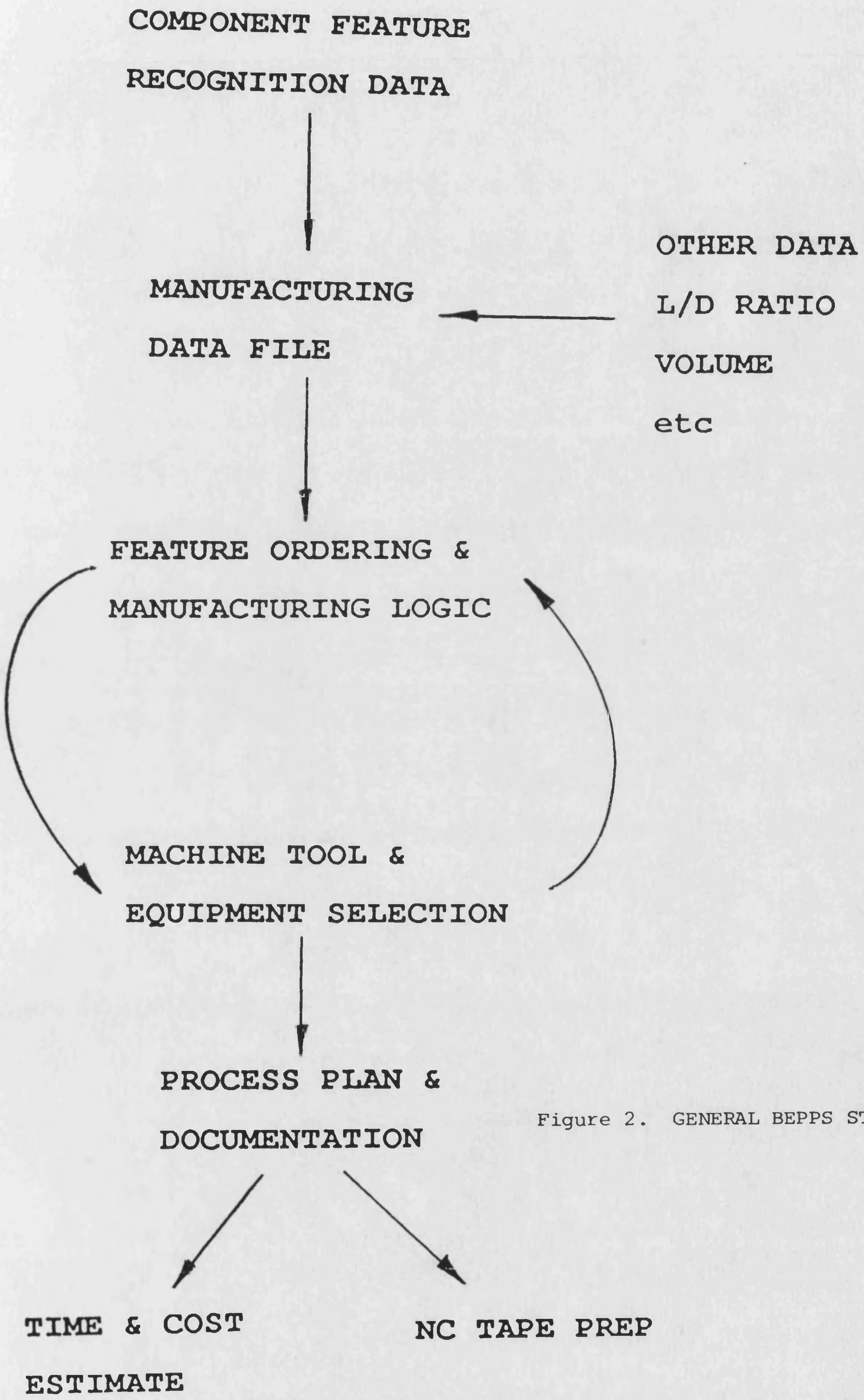

Figure 2. GENERAL BEPPS STRUCTURE

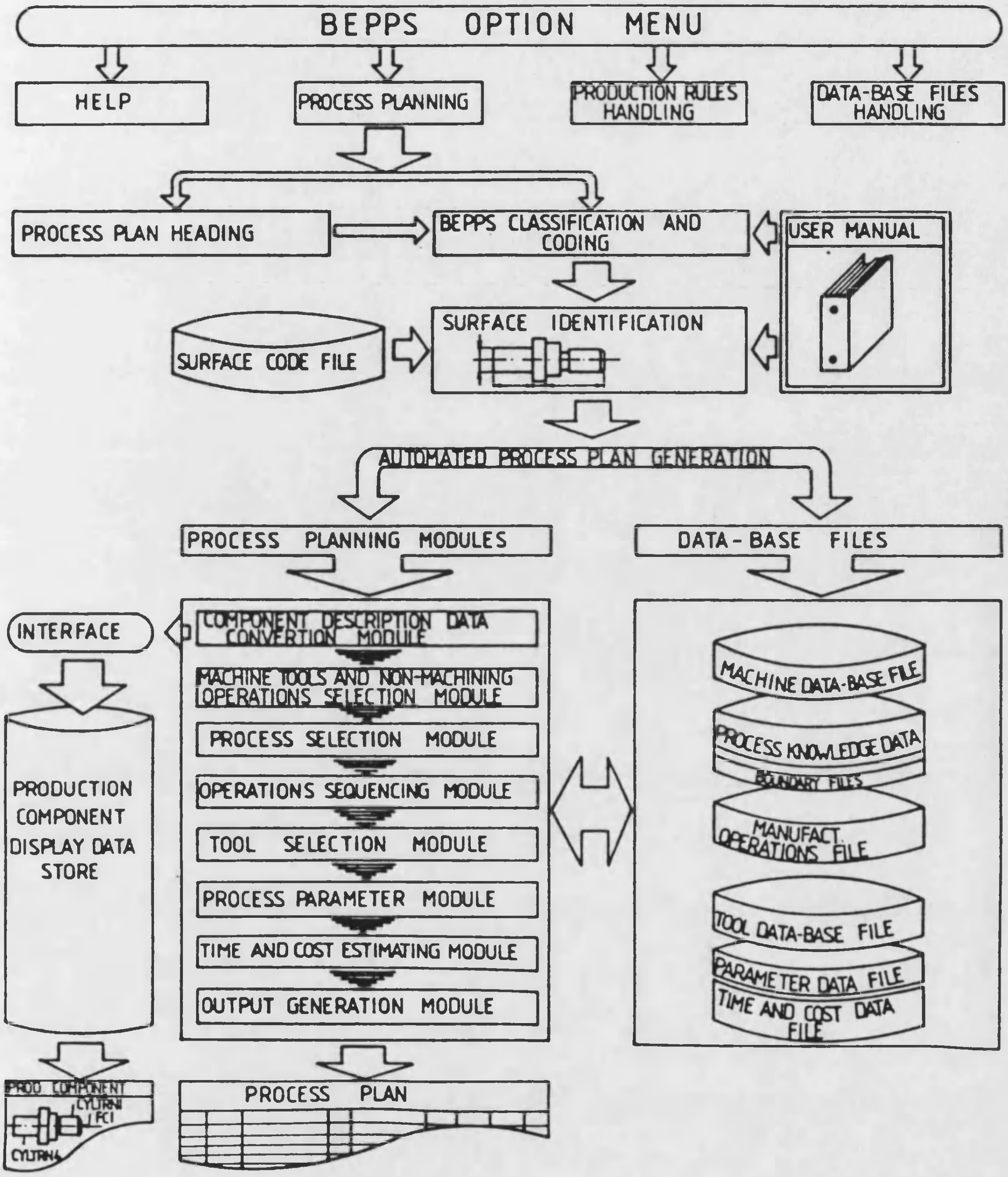

Figure 3. STRUCTURE OF BEPPS TURNING

The Development Of A Generative System Of Computer Aided Process Planning For Prismatic Components (G S C A P P P)

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ABSTRACT

BEPPS is a generative Computer Aided Process Planning (CAPP) system under preparation at the University of Bath. It has been designed with a modular structure that includes modules for conventional machines, NC machines, tooling and fixtures, cost estimating and links to both CAD and production management systems. This paper describes GSCAPPP the module for planning prismatic components on conventional machine tools in a batch manufacturing environment. This module has an interactive input stage designed to elicit component feature and other general manufacturing information. Process plans are then generated automatically using expert manufacturing logic and this plan, together with both tooling and cost estimating information is outputted in the form of a detailed planning sheet. The paper concentrates on the component classification, surface identification and feature recognition techniques used to automate the process planning function.

1. INTRODUCTION

Process planning is an intermediate stage between design and manufacture of a component. It refers to the selection of the procedures required to convert a component design economically and competitively, into a finished product according to the design specification, by determining the method and sequence of machining a component.

Batch production is practiced by more than 75 percent of metal working companies. Manual process planning in such companies has suffered from a shortage of planners, inconsistent planning and a low level of planning, all of which have contributed to the development of computer aided process planning (CAPP) systems.

Under batch production conditions, where lead time is critical, computer integration is difficult to achieve with manual process planning, which is dependent on employees with a great experience in production operations.

Several CAPP systems for non-rotational parts exist using "constructive‘ and "variant" approaches. In the constructive method, the information of the materials, machine tools, cutting tools, operations, ...etc. are held in separate menus in the computer data base. Typically, the planner has to specify the sequence of operations, machines, cutting tools and materials to be used to produce a component. Using a menu structure, the planner selects the relevant page from which to choose the appropriate material, machine, cutting tool and operation from the screen. Once the machine type has been selected, the system will often automatically choose appropriate cutting conditions and then calculate the machining time, and finally output a process planning sheet. The variant method creates a process plan for parts which are related to a specific composite part in a computer data base. The composite part is retrieved and modified to suit the new part and hence a process plan will be created. If components can be grouped into families, the variant approach is valid but it is inefficient if a high variety of parts are required. It can also perpetuate bad plans and tends to be inflexible.

An alternative flexible approach to overcome the shortcomings of these methods is the ‘generative" approach. The objective of this approach is to generate a new process plan for a given part from first principles for each component. Several CAPP systems claim to be based on this approach, but typically they function interactively with high levels of manual decision making. Also several commercial CAPP systems such as: CPLAN [1], LOCAM [2] & SOFIE2 [3] claim that they can be operated in a constructive, variant or generative manner. However, it is doubted whether generative systems will ever be able to deal with parts of real complicated geometry in the near future.

2. GSCAPPP OBJECTIVES

The key objective of this system is to develop a fully automated generative system of computer aided process planning for prismatic type parts, to help fill the gap between CAD and CAM in batch manufacturing. The system is designed to process plan using conventional milling, drilling, boring and grinding machines. The main objectives are:

1. To develop a system which could be used by an unskilled planner who would be required to input component data.

2. To develop an alogrithm for the recognition of the non-rotational component surfaces. Based on this alogrithm, an interactive module, will be built to extract component definition data from an existing CAD system.

3. To develop an internal classification and coding system for the workpiece.

4. To develop a computer program to generate the final output documentation automatically, having all the information required for manufacturing.

3. GSCAPPP LIMITATIONS

Specific boundaries have been used to limit the data bases and logic. These boundaries are:

- The system considers the most common materials used in the batch manufacturing factories for prismatic parts, namely; mild steel, carbon steel and aluminium. Standard shapes and sizes for these materials have been used where possible.

- The system utilises a number of common component features machined on prismatic parts, namely; hole, counterbore, countersink, tap, face, pocket and slot.

- The conventional machines proposed for this system are: horizontal mill, vertical mill, two piller drills, radial drill, vertical boring machine, internal grinder and surface grinder. They have been laid out in a theoretical workshop as shown in figure 1 [4].

- The system utilises a number of specified cutting tools with sizes to match the features and machine tools in the system.

- The workpiece holding devices in this system are considered in outline only.

- The system at present plans only simple prismatic shapes with vertical or horizontal surfaces.

4. GSCAPPP DESCRIPTION

In GSCAPPP, the seven different geometric features can be processed by the system based on the following machining operations:

1. Face milling.	2. Slab milling.
3. Side and face milling.	4. End milling.
5. Drilling.	6. Reaming.
7. Boring.	8. Tapping.
9. Counterboring.	10. Countersinking.
11. Surface grinding.	12. Internal grinding.

4.1 GSCAPPP STRUCTURE

The general structure of GSCAPPP is illustrated in figure 2 [4]. It provides the planner with four initial options: User help, Process planning, Decision logic modification and Data base files modification.

There are 6 main data base files that contain factual information about the machines and tools in the theoretical workshop. The decision logic, and operation sequencing rules have been elicited from industrial case studies and other expert information.

When the decision logic and data bases have been set up, the system is ready to process plan. An interactive input is at present required after which the process plan and output stages are completely automated.

4.1.1 Interactive Stage

In this stage, the planner provides the system with the following input data :

1. General Information:

General information required includes ;

a) Component information (name, number, material & shape envelope).

b) Production information (discrete or continuous).

c) Planner name.

d) Date.

2. Raw Material Data Input:

For development purposes the system considers only standard raw material forms. Of the variety of standard forms and sizes available, this system considers plate, flat and square bar forms in selective sizes. At this stage the planner is asked to input only the material code from the material menu provided by the system.

3. Component Classification & Coding:

A simple classification system has been designed to classify the component with reference to it's size (length, width & height). At this stage the system automatically classes the component into one of the three types and displays the class type for verification by the planner. These classes are :

1- Flat component. A component is considered as flat, if the ratio of the length to the width is less than or equal to 3 and the ratio of the length to the height is greater than or equal to 4.

2- Long component. If the ratio of the length to the width is greater than 3, then the component is classified as long.

3- Cubic component. A component is classified as cubic, if the ratio of the length to the width is less than or equal to 3, and the ratio of the length to the height is less than 4.

It is also necessary for the planner to be familiar with the system devised for coding both the planes and edges that form the shape envelope in which the component lies.

Plane Coding:

Figure 3-A shows a 3-dimensional view of a block, and it's corner coordinates that consists of six surface planes. Generally a plane is named with reference to the axis to which it is normal. eg: x-plane, y-plane or opposite planes as shown in figure 3-B.

A datum plane is a plane in which one corner is set at (x=0, y=0, z=0). An opposite plane is a plane which is parallel to a datum plane at an x, y or z position appropriate to a specific component. It is clear that a component envelope has 3-datum planes and 3-opposite planes. They are coded as follows :

Plane Surface	Plane Axis	Plane Code
	X-axis	XD
Datum	Y-axis	YD
	Z-axis	ZD
	X-axis	XO
Opposite	Y-axis	YO
	Z-axis	ZO

Edge Coding:

The edge code is used to recognise the position of the feature and for determining the machining direction. Edges in GSCAPP are coded according to their plane positions, for example the edges of the x-axis, are named as x-edges and coded as EX0, then moving in an anti-clockwise direction for the next edge EX1, ...etc. Figure 4 illustrates the component edge codes.

4. Feature Data Input:

The features that the planner can input are: plain holes, internal threads, counterbored holes, countersunk holes, faces, slots and pockets.

But before inputting a component's feature information, the planner is required to specify whether the component is simple or complex. In GSCAPPP, a component is considered simple , if the features to be machined are all located on one surface plane, otherwise the component is considered as complex. The system at this stage only plans simple components.

In the case of a simple component, the appropriate plane surface code is required to be inputted by the planner to enable the system to recognise the plane position. A user manual is available to help the planner decide on surface codes. Feature information is then requested. Each feature in the system has a unique code. Several questions are asked by the system so that it can recognise the feature type, size, accuracy, surface finish and position. A menu of features is provided by the system for the planner to enter the feature code. Then by the use of technological logic rules, the system organises these features into a best sequence for machining, ready for the automatic stage of the system.

5. Machine Availability:

The system displays the machine tools (names and codes) so that the planner or production control system are able to delete machines that are currently occupied with other jobs. The system then automatically uses the expert and technological rules to select the appropriate machines from those available, for the operations to be carried out.

4.1.2 Automatic Stage

This is the stage in which process plans are generated automatically from the information provided during the ineractive stage. Process planning is divided into 8 modules :

1) Raw material selection.
2) Feature recognition and ordering.
3) Operation determination and sequencing.
4) Machine tool selection.
5) Cutting tool selection.
6) Cutting conditions selection.
7) Machining time calculation.
8) Workpiece holding device consideration.

The system is automatically routed through each of these modules using the expert rules and factual knowledge in the decision logic and data base files.

4.1.3 Output Stage

When the process plan has been completed in full, it is outputted in the form of a planning sheet that contains the component information, production information, operations determined and their sequences, machine tool set selected, cutting tools selected, cutting conditions determined, time and cost calculated and also indicates the type of workpiece holding device.

5. CONCLUSION

A generative CAPP system GSCAPPP is under development for the automatic planning of prismatic components. The modules forming its structure have been defined. The rules required for planning have been elicited from '*best*' industrial practice and the system has been shown to work in a limited form.

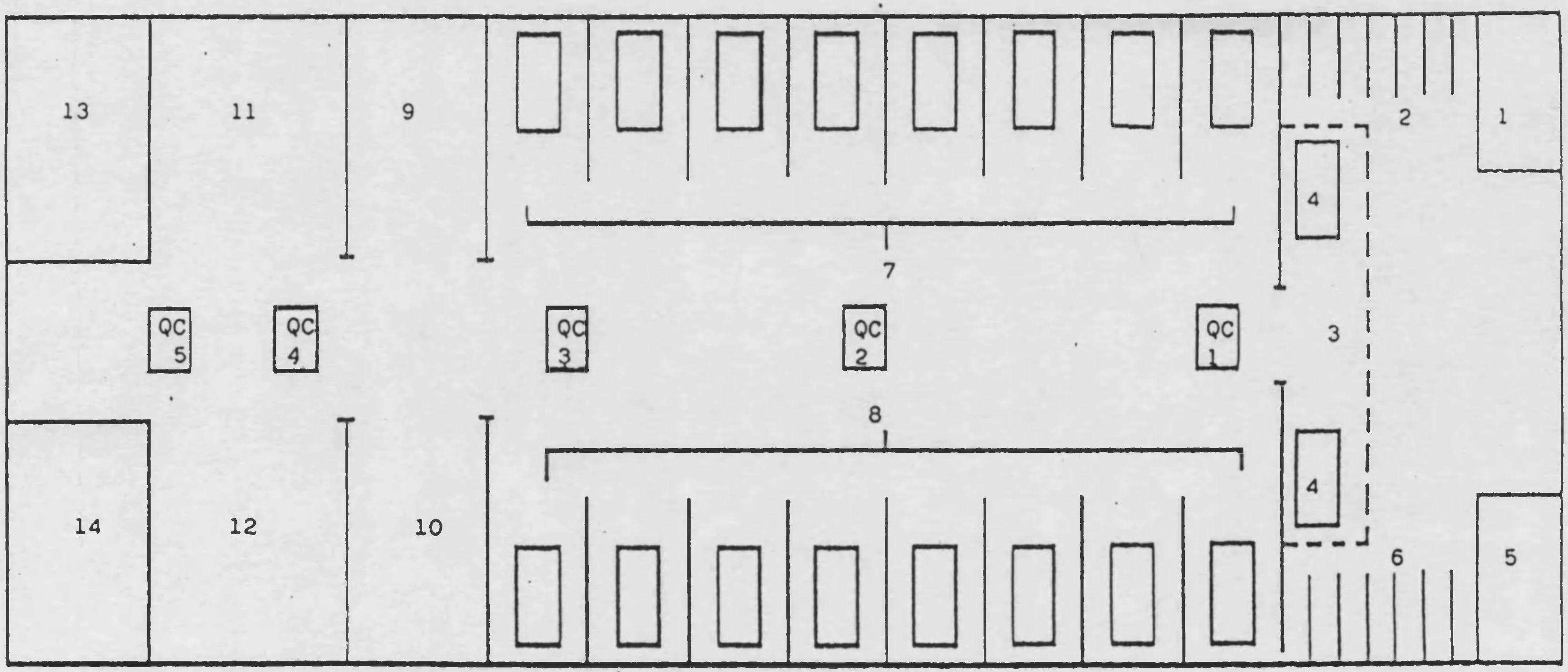
REFERENCES

[1] CPLAN -CADCENTRE, Cambridge, U.K.

[2] LOCAM -PAFEC, Nottingham, U.K.

[3] SOFIE2 -OD Engineering System, Coventry, U.K.

[4] Rustom E.A. PhD Thesis in preparation, University of Bath, U.K.



1. Material Control Room
2. Round Bars Stock Store
3. Sawing to length Zone
4. Sawing Machine
5. Tool Room
6. Sheets, Plates, flat, Square Bars Stock Store.
7. Turning Machines Section. (Rotational Parts Machine)
8. Drilling, Milling, Boring, Grinding Machine (Prismatic Parts Machine)

9 & 10 NC Machines
11 & 12 Assembly Sections
13 & 14 Finished Parts Stores
QC. Quality Control Station

Figure 1 : General Organisation of a Machine Shop for BEPPS

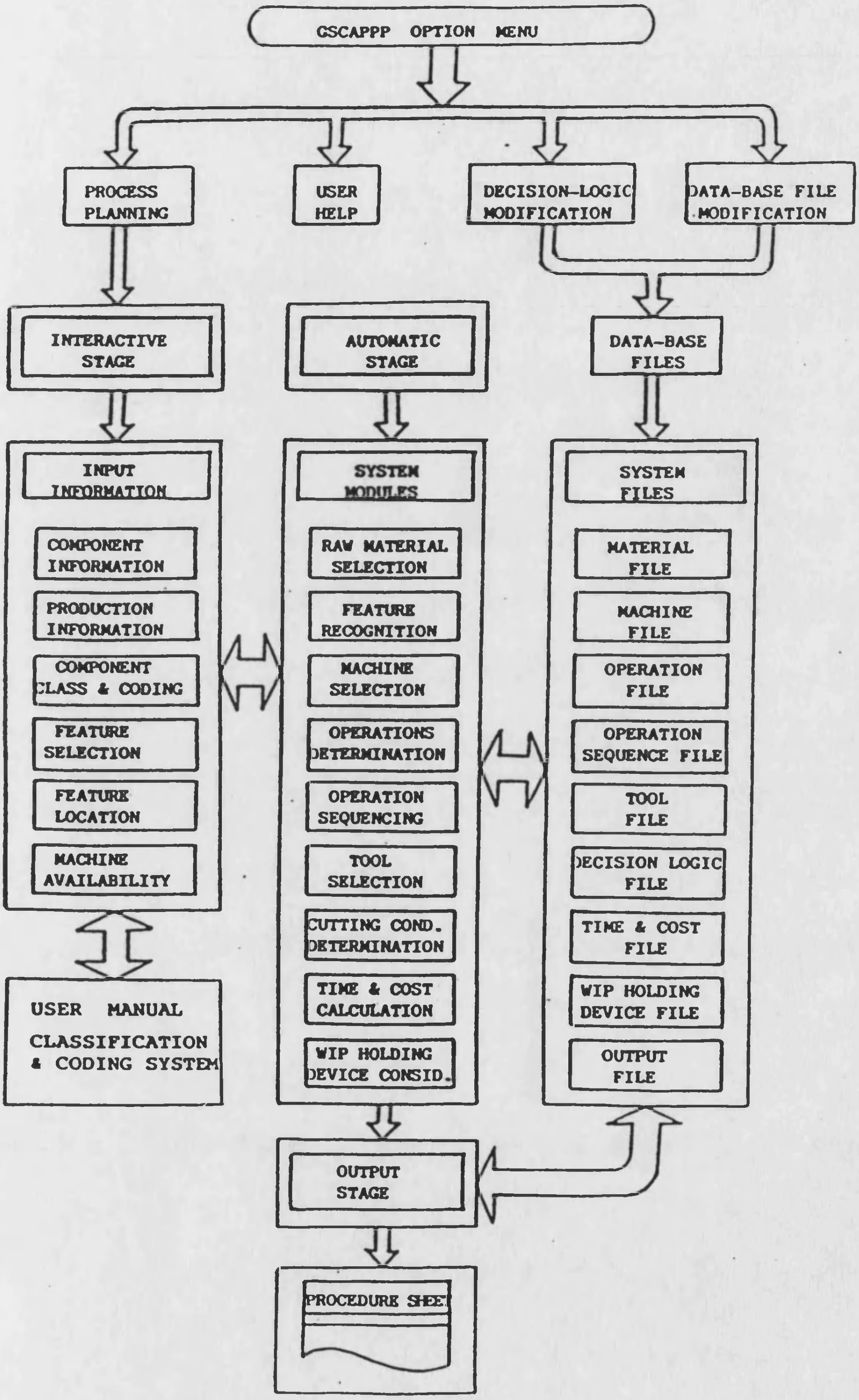


Figure 2 : GSCAPPP General Structure

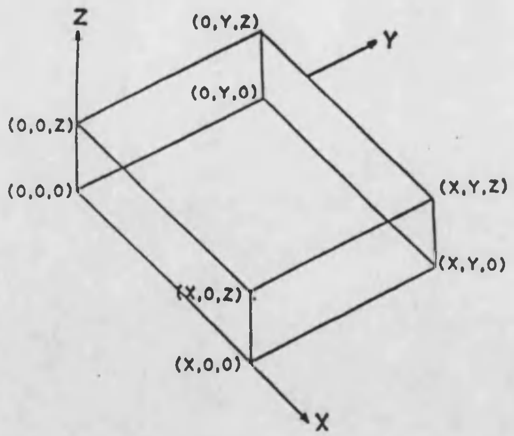


Figure 3 - A : Corners Coordinates in the Component

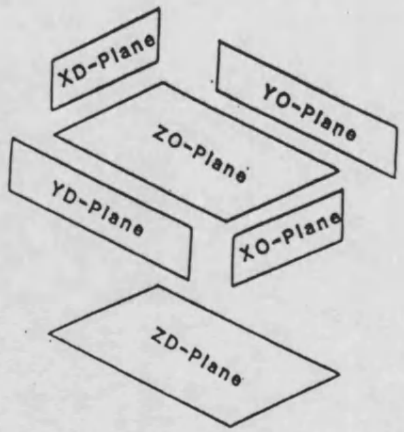


Figure 3 - B : Datum & Opposite Plane of a Component

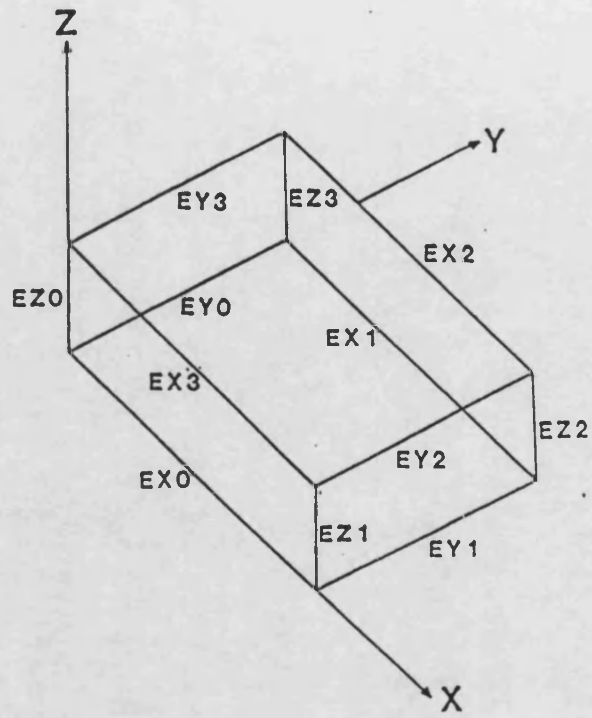


Figure 4 : Edge Codes of a Component

The Development Of A Generative Computer Aided Process Planning System For Prismatic Components

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ABSTRACT

BEPPS is a generative Computer Aided Process Planning (CAPP) system under preparation at the University of Bath. It has been designed with a modular structure that includes modules for conventional machines, NC machines, tooling and fixtures, cost estimating and links to both CAD and production management systems. This paper describes GSCAPPP the module for planning prismatic components on conventional machine tools in a batch manufacturing environment. This module has an interactive input stage designed to elicit component feature and other general manufacturing information. Process plans are then generated automatically using expert manufacturing logic and this plan together with both tooling and cost estimating information is outputted in the form of a detailed planning sheet. The logic required to plan the manufacture of holes is concentrated on.

INTRODUCTION

Manufacturing industry in the UK, has in recent years, had to respond to an increased demand for products of higher quality and variety made at an internationally competitive price. To achieve increased competitiveness and integration companies have invested in computerization. Under batch production conditions, where lead time is critical, computer integration is difficult to achieve with manual process planning, which is dependent on employees with a great experience in production operations.

Batch production is practiced by more than 75 per cent of metal working companies. Manual process planning in such companies has suffered from, a shortage of planners, inconsistent planning, and a low level of planning, all of which have contributed to the work on developing Computer-Aided Process Planning (CAPP) system.

A number of CAPP sytems for non-rotational parts exist using "constructive' and "variant' approaches. In the constructive approach, the information of the materials, machines, tools, operations, ...etc. are held in separate menus in the computer data base. Typically, the planner has to specify the sequence of operations, machines, tools and materials to be used to produce a component. Using a menu structure, the planner selects the relevant page from which to choose the appropriate material, machine, tool and operations from screen. Once the machine type has been selected, the system will often automatically choose appropriate cutting conditions and then calculate the machining time, and finally output a process planning sheet. The variant approach creates a process plan for parts which are related to a specific composite part in a computer data base. The composite part is then retrieved and modified to suit the new part and hence a process plan will be created. If components can be be grouped into families, the variant approach is valid but it is inefficient if a high variety of parts are required. It can also perpetuate bad plans and tends to be inflexible.

An alternative flexible approach to overcome the shortcomings of these methods is the "generative' approach. The objective of this approach is to generate a new process plan for a given part from first principles for each component. Several CAPP systems claim to be based on this approach, but typically they function interactively with a high level of manual decision making. Also several commercial CAPP systems such as: CPLAN [1], LOCAM [2] & SOFIE2 [3] claim that they can be operated in a constructive, variant or generative manner. It is doubted whether generative systems will ever be able to deal with parts of complicated geometry.

1. SYSTEM OBJECTIVES

The key objective of this work is to develop a fully automated generative system of computer-aided process planning for prismatic type parts, to help fill the gap between CAD and CAM in batch manufacturing.

The system is designed to process plan using conventional milling, drilling, boring and grinding machines. The main objectives are:

1. To develop a system which could be used by an unskilled planner who would be required to input component data.

2. To develop an alogrithm for the recognition of the non-rotational component surfaces. Based on this alogrithm, an interactive module, will be built to extract component definition data from an existing CAD system.

3. To develop an internal classification and coding system for the workpiece.

4. To develop a computer program to generate the final output documentation automatically, having all the information required for manufacturing.

2. SYSTEM STRUCTURE

GSCAPPP has been designed with a modular structure and the following have been identified as the main modular elements.

1. Input information.
2. Raw material selection.
3. component classification and surface coding.
4. Feature data input.
5. Machine availability.
6. Process planning: (which is subdivided into)
    a) Raw material selection from stock.
    b) Feature recognition.
    c) Machine selection.
    d) Operation determination and sequencing.
    e) Tool selection.
    f) Cutting condition determination.
    g) Machining cost and time calculation.
    h) Workpiece holding device consideration.
7. Output procedure.

3. SYSTEM LIMITATIONS

Specific boundaries have been used to limit the data bases and logic. These boundaries are:

- The system considers the most common materials used in the batch manufacturing factories for prismatic parts; namely, mild steel, carbon steel and aluminium. Standard shapes and sizes for these materials have been used where possible.

- The system utilises a number of common component features machined on prismatic parts, namely: hole, counterbore, countersink, tap, face, pocket and slot.

- The conventional machines proposed for this system are: horizontal mill, vertical mill, two piller drills, radial drill, vertical boring machine, internal grinder and surface grinder.

- The workpiece holding devices in this work will be considered in outline only.

4. SYSTEM DESCRIPTION

The general structure of GSCAPPP is illustrated in figure 1 [4]. It provides the planner with four initial options: User help, Process planning, Decision logic modification and Data-base files modification.

The main option is process planning which is divided into three stages: Interactive, Automatic and Output stages. In the interactive stage, the planner provides the system with the input data required to generate the process plan. The automatic stage selects the appropriate raw material from stock together with the required machines and cutting tools. It also determines the operations, their sequences, the cutting conditions and calculates the machining time. The workpiece holding device is also considered in this stage. The final stage is the output, which lists general information about the component and production in addition to the process plan route.

4.1 PRODUCTION OF A HOLE IN SOLID MATERIAL

This paper concentrates on the logic required to plan the manufacture of holes.

4.1.1 HOLE INPUT INFORMATION

The information required for the production of holes is inputted interactively and the following data is requested.

a) Is the hole a through hole or blind hole.

b) Hole diameter (a value between 0.3 mm and 75.0 mm is required).

c) Hole depth in mm.

d) Hole surface roughness (the CLA values possible are restricted).

e) Hole accuracy. The planner is requested to select one of four options:

1) No special accuracy. 2) Diametral accuracy.

3) Centre accuracy. 4) Diametral & centre accuracy.

(Note taper and parallelism have not been included in the system as yet)

f) Hole centre coordinates. This is specified with reference to the plane on which it lies.

4.1.2 HOLE PRODUCTION LOGIC

When the input is complete, the system uses decision logic to generate the process plan automatically. A decision tree is used to systematise the decisions required and the tree used for the production of holes in solid blocks [4] is detailed in figure 2. The rules on which the decision logic is based have been elicited from '*best*' industrial practice.

Rules have been extracted from both examples and questionnaire answers. Best practice has been used because of the high level of disagreement between planning experts. For example the plan for a 25.0 mm diameter hole in mild steel with a tolerance of +/- 0.25 (low precision) varied from:

a) Centre drill -drill (25.0).

b) Centre drill -pilot drill 1. -pilot drill 2. -drill (25.0).

route (a) being prescribed by a successful high precision machine tool company. One company had the policy of reaming / boring all holes as they considered that this gave better quality regardless of function. In another area of disagreement a major motor manufacture machines all holes in cast iron and aluminium without the use of centre drills regardless of size, while almost all other companies surveyed used centre drills even for 1.0 mm diameter holes. Most companies also have a maximum drill diameter after which they drill and then bore. As a general rule this is 75.0 mm.

Despite the conflict between experts, rules have been devised and coded in the form of:

IF(condition) THEN(action), statements.

For example:

IF(HT.EQ.TH.AND.HD.GE.8.0.AND.LT.15.0.AND. .....)
THEN(CD, DRILL, REAM)

When a route has been specified the system then automatically selects the appropriate machine tool set and cutting tools and then determines the operation sequence, cutting conditions and machining time.

4.1.3 OUTPUT SHEET

The final module enables a fully documented process planning sheet to be produced for shop floor issue with a conventional heading that includes the general component details.

CONCLUSION

A generative CAPP system, GSCAPPP is under development for the automatic planning of prismatic components. The modules forming it's structure have been defined. The rules required to plan holes have been elicited from industry and encoded such that holes can be planned effectively.

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[1] CPLAN -CADCENTRE, Cambridge.

[2] LOCAM -PAFEC, Nottingham.

[3] SOFIE2 -OD Engineering Systems, Coventry.

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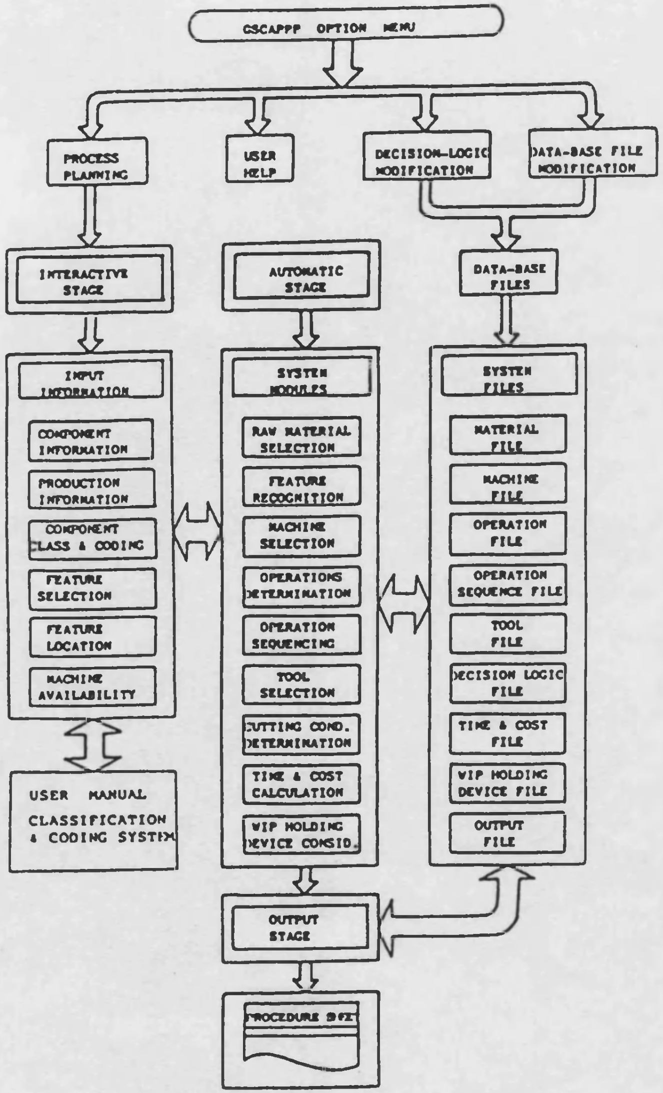

FIGURE 1 GSCAPPP GENERAL STRUCTURE

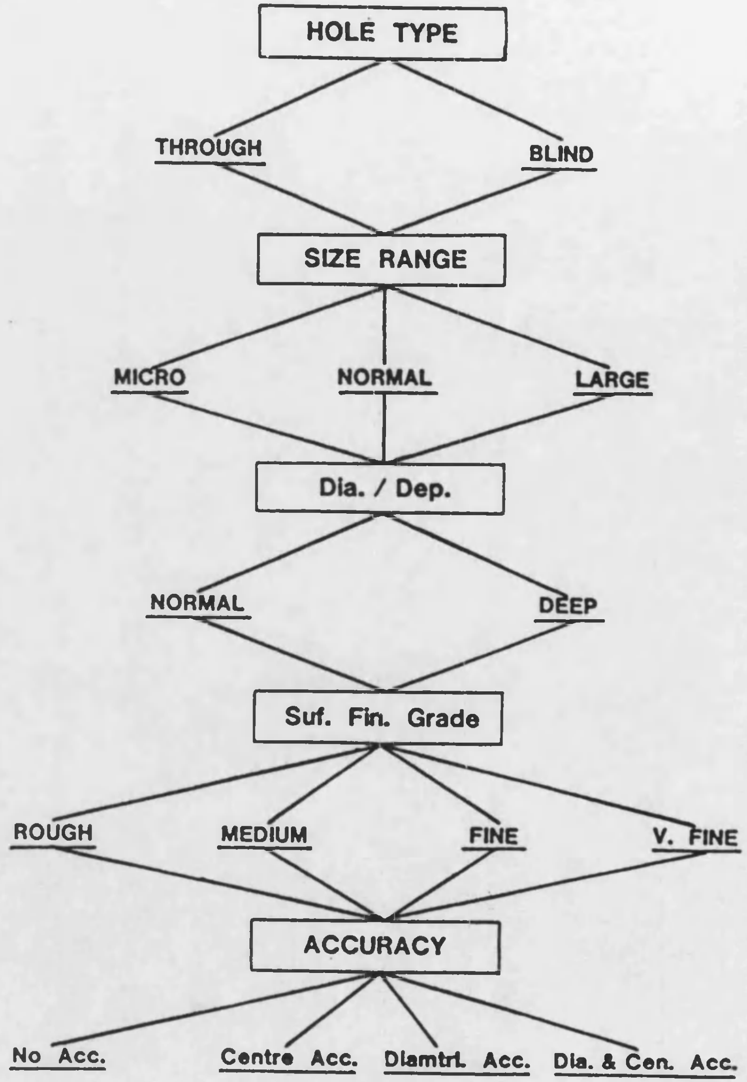

FIGURE 2. DECISION TREE FOR HOLE PRODUCTION

Automatic Selection Of Raw Material In Process Planning

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ABSTRACT

GSCAPPP is a Generative System of Computer Aided Process Planning for Prismatic components under development at the University of Bath. It has been designed for planning prismatic components on conventional machine tools in a batch manufacturing environment. This Paper concentrates on the module for the automatic selection of raw material. This module is divided into two stages, the material type stage and the material supply stage. In the material type stage the planner is required to choose the material specification from a restricted list of material types. The material supply stage then gives the planner the choice of opting for a range of standard forms or for specials that are supplied in the form of casting, forging ... etc. If a standard material form has been specified the system automatically selects the most appropriate size and shape of raw material to use. The paper discusses in detail the rules and logic that have been used to accomplish this automatic selection and how this information is then used for the subsequent generation of process plans.

1. Introduction

The function of computer aided process planning (CAPP) is to determine the process plan for a component by computer. To manufacture a component, a series of different processes must be performed on the raw material stock. These process steps are defined as process planning, which includes all the decision making activities and preparation work that is necessary to produce a component to its design specification.

A number of both commercial and research CAPP systems have been put forward which have been typically based on either a constructive or variant approach together with a level of generative capability. The systems that are partially generative, have concentrated, in general, on the automatic selection of the procedures required to convert a component design into a finished product by determining the method and sequence of machining a component.

Within these systems the selection of appropriate raw material, in general has not received any significant attention. The notable exception to this was reported in a system called GIPPS [1], in which a raw material selection module had been designed for a specific company and hence a limited range of components. The planner was asked to choose the basic raw material shape ie. plate, bar, ... etc. and after this had been specified the system automatically selected a raw material stock size. This system also tried to include the economics of stock preparation and the difference in standard raw material costs. It is claimed that significant benifits were gained by the company after the system was introduced.

The main aim of GSCAPPP is to generate process plans for prismatic components with a high level of automation. The output is intended to produce a detailed process plan together with the most appropriate raw material form selected from a defined range. This paper concentrates on the methodology and logic that has been adopted to achieve the automatic selection of raw material.

2. General Structure and Data Input

GSCAPPP contains three main mdules; Input, Process Planning and Output, together with facilities for updating logic and the data bases.

The data input enables all of the subsequent decisions to be made automatically by the system, including the selection of the raw material form. It has been designed to take in the required geometric and technical information for each component that requires planning. This information is recorded in a component data file that can be accessed as required by the sub-module at the planning stage. The input information is divided into three types:-

1. General component data.
2. Information for component classification and coding.
3. Geometric data that enables component feature identification.

2.1 General Data:-

When the system is being used the planner is interactively requested to input answers to a variety of general questions, that includes:

The components description,
part number,
material specification,
overall shape envelope size (length, width & depth).

Production information detailing the batch type ie. discrete or continuous,
the batch size.

The Planners name.

The Planning date.

2.2 Classification and Coding:-

A simple system has been devised to classify components by their overall shape envelope. From the length, width and depth inputted by the planner, each component is designated as belonging to one of three different classes; Flat, Long or Cubic [2]. A component is considered as flat, if the ratio of the lenght to width is less or equal to 3 and the ratio of the length to the depth is greater or equal to 4. If the ratio of the length to the width is greater than 3, then the component is classified as long. A component is classified as cubic, if the ratio of the length to the width is less or equal to 3, and the ratio of the length to the depth is less than 4. Figure 1 shows the component envelope and class.

As well as this simple shape classification a system of coding a components planes and edges has been used. In general, plane code depends on the corner coordinates of the shape envelope as shown in figure 2-A. A plane is identified with reference to the axis to which it is normal and for each axis there are two types of plane that can be specified, datums and opposites. A datum plane is in turn specified as a plane in which X, Y or Z coordinates of its corners are all equal to zero. Alternatively an opposite plane is defined as being parallel to a datum plane and set at a given distance from it. Figure 2-B shows the datum and opposite planes of the component.

During the input stage the planner is required to specify the planes on which machining will take place in terms of a set of plane codes [3]. At this point the computer displays the components class on screen for a visual check to take place.

2.3 Feature Identification:-

For research purposes the features in GSCAPPP are limited to include the most common ones that are machined on prismatic components namely; plain holes, stepped holes, countersinks, threads, flat surfaces, pockets and slots. The planner in this stage is requested to input the feature codes and locations together with the finishing requirements.

3. GSCAPPP Raw Material

The raw material selection module is a sub-module of the processes planning module and for the research purposes it has been restricted in size. It has for example a limited range of raw material types; mild steel, carbon steel and aluminium. Although it is also considered that this limited range covers the majority of prismatic components machined from stock. The system is based on of small batchworking shop that only machines components from stock and only keeps in stock a small range of standard shaped bars ...etc. This information is contained within files in one of the data bases of GSCAPPP. Each file contains stock dimensions and each stock size has been given a unique code that enables faster data mainapulation. When a stock size has been automatically selected the system displays the stock dimensions and code on screen for the planner to visually check. The code has a combined alphanumeric form which indicates material type, shape classification and size. For example MF2.5X30 is a flat mild steel bar of 25.00 X 300.00 cross section.

3.1 Raw Material Information Retrieval and Analysis:-

When during the input stage the shape envelope dimensions are requested, the planner is asked to input the largest dimension as the length and the smallest as the depth. If any two dimensions are the same then they are requested as length and width if they are large ...etc. However the system has sufficient logic to check these dimensions and reorder them if an input error has occured. As stated the dimensions are then displayed with correct notation for the planner to make a visual check.

When the overall dimensions have been verified and the feature and plane information inputted; the system checks to establish what if any material allowances are required in order to achieve the tolerances and finishes specified. This is carried out as part of the process planning module and uses expert logic to make the required decisions. By using a metal addition technique the system changes the shape envelope of the finished component into the shape envelope of the raw material. At this stage the system also determines whether or not the raw material tolerances are sufficiently accurate to negate machining of any of the required planes.

3.2 Selection of Raw Material Form:-

As described above during the analysis stage of process planning the shape envelope of the raw material is determined. This forms the base information for selecting the most appropriate raw material form. The data base of standard forms assumes at present that each bar etc. is substanially longer than any component that the system can accommodate, hence only X and Y dimensions are important. A "best‘ fit comparison is then carried out in order to match a components shape envelope with the material X Y dimensions. Basically the components Length/Width, Length/Depth and Width/Depth are compared against all X Y material dimensions of the stock held. If there is an exact match, the matching algorithm is stopped and the material stock designated as the ‘Ideal Form" ie. no excess machining is required.

If no ideal form is available, then the data base is searched to find the nearest fits. These are displayed on the screen together with the most appropriate stock size. The most appropriate stock size is arrived at automatically by taking into account, the minimum volume of excess metal to be removed, the minimum contact area for machining, and the method of removing the excess metal. By using these three factors it is considered that the choice of the most appropriate stock size is based on a combination of minimum volume and economics. If for some reason outside the normal logic, a different stock size is required then the planner can override the system and specify the raw material form for further processing. Figure 3 shows the structure of the material selection module.

3.3 Output of the Raw Material Selection Module:-

Once the system has analysed the parameters and chosen the most appropriate form, the information is transferred to the 'cut to length" module to select a cutting operation i.e. sawing or burning. After this has been selected the information is put into the output file ready for printing onto the planning sheets which is outputted when the process planning has been completed. It is also made available for use during feature ordering and operation selection, ...etc.

4. Conclusion

A raw material selection module has been developed that will choose the most appropriate stock size available. The decision logic used takes into account the overall economics in comming to a decision. It is considered that advantages could also be gained by using the module as a stand alone package in a design for manufacture environment.

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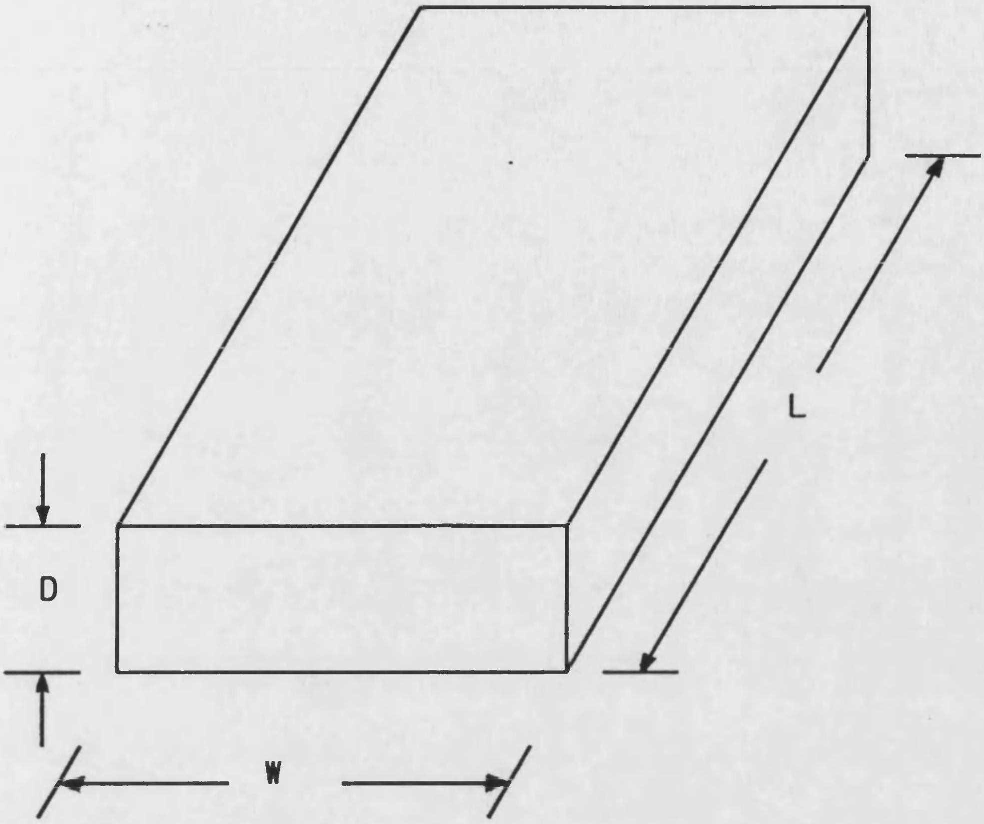

1. $\frac{L}{\mathbf{W}} \leq 3$ & $\frac{\mathbf{L}}{\mathbf{D}} \geq 4$ .... *Flat component.*

2. $\frac{L}{\mathbf{W}} > 3$ .... *Long component.*

3. $\frac{L}{\mathbf{W}} \leq$ & $\frac{\mathbf{L}}{\mathbf{D}} < 4$ .... *Cubic component.*

Figure 1 Component Class.

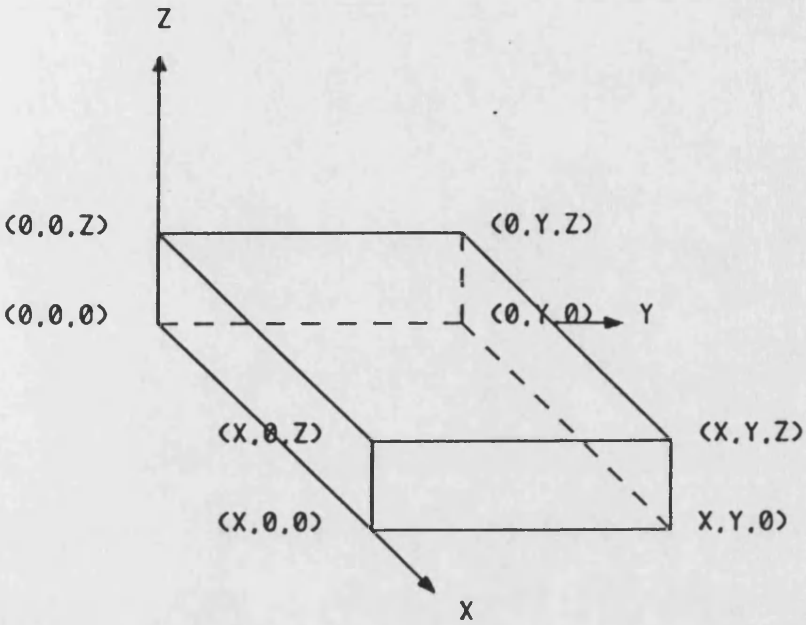

Figure 2-A Corners Coordinates in the Component.

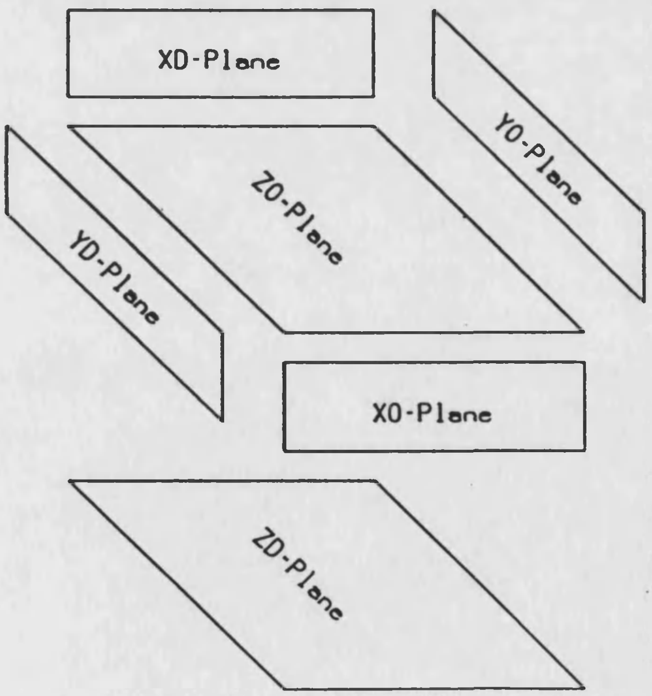

Figure 2-B Datum and Opposite Planes of a Component.

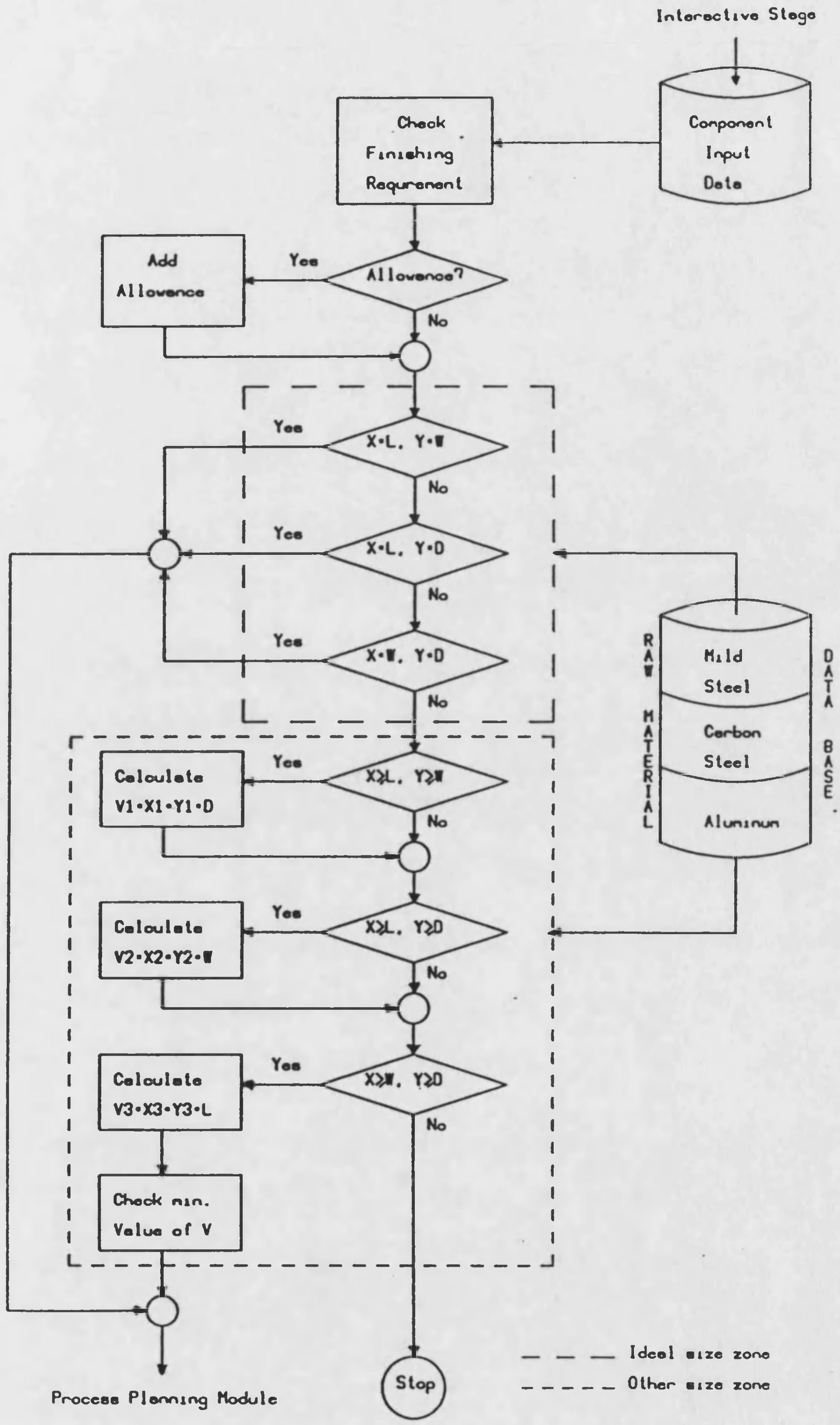

Figure 3 Structure of Raw Material Selection Module.

Feature Ordering & Operation Sequencing For Automated Process Planning

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ABSTRACT

GSCAPP is a Generative System of Computer Aided Process Planning for Prismatic components under development at the University of Bath. It has been designed for planning prismatic components on conventional machine tools in a batch manufacturing environment. This paper describes the feature ordering and operation sequencing modules. The simplified research version uses 7 features that are divided into two main groups, the flat group which includes flat surface, pocket and slot, and the cylindrical group which includes plain hole, stepped hole, countersink and thread. The system recognizes these features from their codes, gives them a priority value, and puts them in order for machining using expert industrial rules. The operations required to machine the features are then divided into two stages, the primary operations stage and finish operations stage. The primary operations stage includes the rough, and semi-finishing operations (the operations which do not required high precision machine tools), while the finish operations stage includes the operations in which the component features require a high quality of surface finishing and accuracy. The modules have been tested over a range of components and the results indicate that the logic is valid with effective process plans being generated.

1. Introduction

The main task of computer aided process planning (CAPP) is to determine the sequence of the individual processing operations needed to produce a finished component according to the design specification.

A number of both commercial and research CAPP systems have been put forward which have been typically based on either a constructive or variant approach together with a level of generative capability. The systems that are partially generative, have concentrated, in general, on the automatic selection of the operations required to produce individual component features. Although feature ordering is perhaps the most important element to automate in a generative CAPP system, it has not, as yet, been satisfactorily included in any current CAPP system. However the process plan for a component should not only include the sequence of operations for producing individual features but should contain the order in which features are to be processed and whether features are to be processed individually or in combinations.

In variant CAPP systems the feature ordering information is fixed within the "standard" plans, whereas in generative systems expert precedence rules, based on the various constraints, must be formulated and embedded into the computer system. Today most of the valid CAPP systems for prismatic parts have either used rules that have been applied interactively by the user (Eskicioglu) or automatically using very simple conditions (Chang & Wysk). PC-CAPP (S.Pande & M.Walvekar) claims to generate plans for prismatic components but there is little indication of the level of interactivity for feature ordering or the constraints placed upon the system in terms of component shape etc.

The aim of GSCAPPP is to move progressively towards the situation in which process plans are generated automatically. This paper looks at the automation of the feature ordering process and to achieve this a range of common prismatic features have been selected together with the appropriate logic rules associated with batch manufacturing companies.

2. Component Features in GSCAPPP

The features in GSCAPPP have been purposely limited during the research to include the most common features found on prismatic components, namely; plain holes, stepped holes, countersinks, threads, faces, pockets and slots. As a further limitation only flat horizontal and vertical faces have been included.

2.1 Feature Classifications

The seven feature types have been classified into two major groups; flat and cylindrical according to the tool geometry and motion required to machine them. The flat group includes faces, pockets and slots and the cylindrical group includes plain holes, stepped holes countersinks and threads. Each group is then subdivided into basic and secondary features as shown in figure 1. This classification has been designed to give a much simpler feature ordering descision logic and to group features requiring the use of the same machine tool type.

2.2 Feature Data Input

At present the feature data is inputted interactively by the planner via system promts. Initially the planner is asked to choose one of the three main options after studying the component to be planned.

These are i. Flat features only required.
ii. Cylindirical features only required.
iii. Both Flat and Cylindrical features required.

Once the choice has been made the system then displays the range of features within the group for the planner to choose the appropriate feature set. In the case of choice (iii) information on the flat features is requested prior to that for the cylindirical features. For each feature, the planner is asked for a variety of parameters including, feature code, location, dimensions, tolerances, surface requirements etc. This data is stored in a component data base file that can be retrieved and processed for several functions including the feature ordering. It is also intended to eventually accept feature information via CAD and the component data file has been constructed accordingly.

2.3 Feature Ordering

Each feature is given a score based on it's 'priority' in machining. This score can be increased depending on whether or not certain logic conditions are met. The logic conditions refer to such factors as feature location, finishing conditions, machinability, ...etc. The hierachy of features shown in figure 2 gives the basic score order for both flat and cylindrical groups. The flat group for example typically has priority over the cylindrical group. This will result generally in plans showing Mill and then Drill i.e a hole will not be machined unless the face on which it is located has been completed. Logic is also being developed to predict using both tooling and orientation restraints under what circumstances similar features on different surfaces should be grouped into consecutive operations. In general the rules adopted have been taken from good industrial practise.

From the data input, the computer system automatically recognises the feature types gives them each a score according to their basic and special conditions and then orders them for machining. The logic developed to date, concentrates on the intra group order within the main feature groups. It is of interest however that for many components, the feature order given by basic scores gives an acceptable process plan.

3. Operation Sequencing

Once the features have been put into a correct order for processing, the operations to produce the features must then be included in the correct sequence. The operations themselves are divided into the machining and non-machining operations required to produce a particular feature or feature group. The non-machining operations include, machine tool set-up, loading and unloading, cleaning and quality checks.

The machining operations are subdivided according to their capability, into rough or semi-finishing operations, which typically can be carried out on standard milling , drilling and boring machines or finishing operations where for example, grinding or honing machines are used.

The computer system automatically selects the appropriate machine tools from the data base that will allow the required operations to be carried out paying due regard to operation groupings and tool capability.

The result is an automated process plan in which features are ordered with regard to a variety of rules and restraints and in which the operations required to produce the individual features and feature groups are effectively sequenced.

The system has been satisfactorly tested over a range of simple components and is now being extended to accommodate greater component complexities.

4. Conclusion

An initial methodology for the automatic feature ordering and operation sequencing of prismatic component features has been developed. This has been successfully applied to simple components that can be described by up to 7 basic feature types. The feature ordering relies on allocating a priority score to individual features depending on their basic priority and any special modifying considerations.

The initial methodology is considered to be effective and now is being extended to take in greater complixities.

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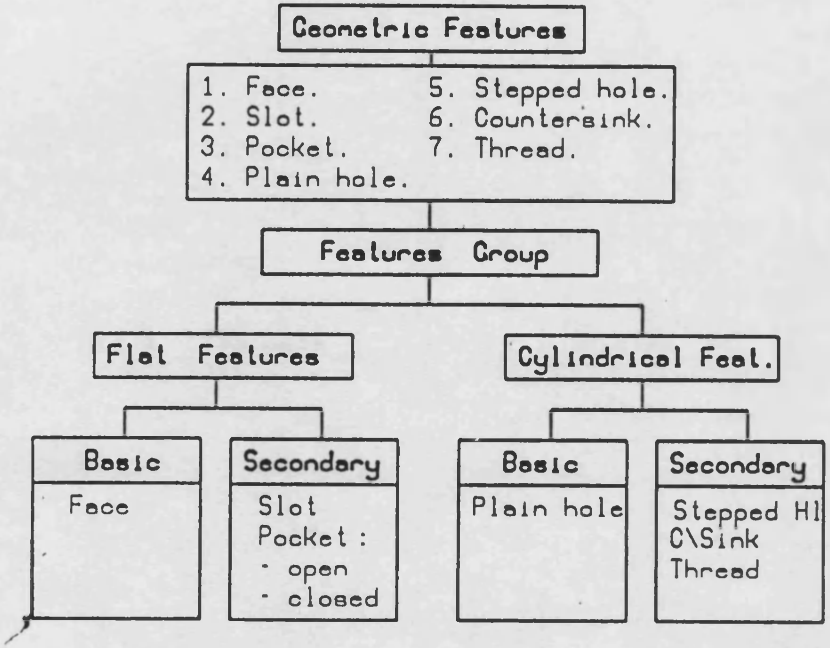

Fig. 1 GSCAPPP Features Classification

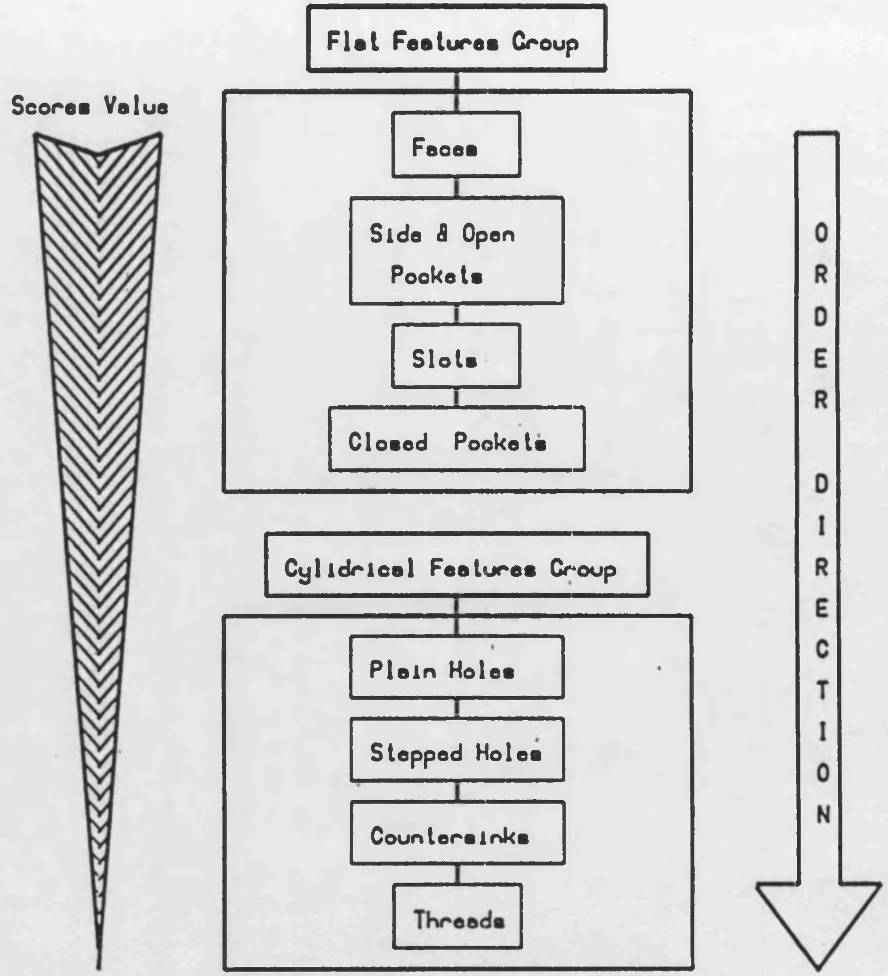

Fig. 2 GSCAPPP Feature Ordering Hierachy

Automated Decision Making For Process Planning

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ABSTRACT

BEPPS-GSCAPPP is a generative System of Computer Aided Process Planning for Prismatic components under development at the University of Bath. It has been designed for planning prismatic components on conventional machine tools in a batch manufacturing environment. This paper describes the program structure and details two main modules. Firstly the interactive input stage is described, which is designed to elicit component feature and other general manufacturing information. Secondly it focuses on the automatic stage concentrating on the automatic selection of raw material from a restricted list of standard material types stored in the material data base and follows by describing how feature ordering of the 7 common features has been automated by grouping them into flat and cylindrical groups and then prioritising them in a novel way to achieve a best order for machining.

1. INTRODUCTION

Process planning is an important activity that links the design and manufacture activities in the component cycle. It involves the selection and sequencing of the operations and processes required to convert a component design economically and effectively into a finished.

Traditionally process plans are generated manually and are documented on route sheets that specify both the processes and the machines to be used. This function is usually carried out by an expert planner who is highly skilled in the decision making aspects and has great experience of shop floor operations. The major disadvantage of manual process planning is inconsistency [1]. It is not unusual for different planners to specify different routes for the same part, each expressing their own preference. Further there is no way of being sure that any route is optimal and thus the level of planning proficiency will affect the efficiency of manufacturing.

The computer offers potential for reducing routine clerical work, and at the same time, it is capable of calculating complicated formula and analysing logic rules in a much faster time. Process planning systems which are assisted by computer power are called computer aided process planning (CAPP) systems.

Literature reveals that four typical approaches have been put forward for computer aided process planning (CAPP). (1) The *Constructive* approach in which the information of the materials, machines, tools, operations ...etc. are held in separate menus in the computer data base. Typically, the planner has to specify the sequence of operations, machines, tools and materials to be used to produce a component. Using a menu structure, the planner selects the relevant page from which to choose the appropriate material, machine, tool and operations from the screen. Once the machine type has been selected, the system will often automatically choose appropriate cutting conditions and then calculate the machining time, and finally output the process planning sheet. (2) The *Variant* approach creates process plans for parts which are related to a specific composite part in a computer data base. The composite part is then retrieved and modified to suit the new part and hence a process plan is created. (3) The *Generative* approach generates a new process plan for a given part from first principles. The system uses information which is available in a manufacturing data base that contains the part description data and technological information. Using expert process decision logic the computer program manipulates the data in order to automatically generate a process plan. (4) The *Expert System* approach is a new form of generative process planning that uses an expert system program structure to make the planning decisions. Expert planning systems are currently being researched [2], [3].

2. GENERAL STRUCTURE OF GSCAPPP

BEPPS-GSCAPPP is a knowledge-based Generative System of Computer Aided Process Planning for Prismatic components. It has been designed with a modular structure. The general structure of BEPPS-GSCAPPP is illustrated in figure 1 [4]. Basically it contains four options; (1) User's help, (2) Process Planning, (3) Decision logic modification and (4) Data base file modification. The user's help option provides general guidance on how to use the system at the initial stage. In option (3) and (4), the user can have access to both decision logic and data base files to enable updating and/or modification whenever it is required. The main option is process planning which is divided into three further stages; *Interactive* stage, *Automatic* stage and *Output* stage.

2.1 Interactive Stage:

In this stage, the planner provides the system with the input data required to generate the process plan. Input data is subdivided into five sections. i. General information data input, ii. Component classification and coding, iii. Component type, iv. Machine availability, and v. Feature data input.

2.1.1 General Information Data Input: In this section the planner is asked to input general information about the component and the production plan. The component information includes; component's name, number, material and shape envelope (length, width and depth). The planning information includes the batch type (discrete or continuous), the planner's name and date.

2.1.2 Component Classification and Coding: The system at present only considers only standard raw material forms with plate, flat, and square bar forms in selective sizes only being included. It is necessary for the planner to be familiar with the system devised for coding both the planes and edges that form the shape envelope in which the component lies. As the system is designed for prismatic components, it is important to code the surface planes in a certain way, as this enables the planner to input the features in a distinct order for each plane.

2.1.2.1 Plane Coding: Generally, a plane is named with reference to the axis to which it is normal i.e. (X-plane, y-plane, or z-plane). The six surface planes of the component are divided into two types; *Datum Planes*, and *Opposite Planes*. A datum plane is a plane in which one corner is set at (x=0, y=0, and z=0). An opposite plane is a plane which is parallel to the datum plane at an x, y, or z position appropriate to a specific component. Figure 2 shows the six plane surfaces with their codes.

2.1.2.2 Edge Coding: The edge code is used to recognize the position of each feature and for determining machining direction. Edges in GSCAPPP are coded according to their plane positions. For example, the edges of the x-axis, are named as x-edges and coded as EX0 for the original x-axis, then moving in an anti-clockwise direction for the next edge EX1, ...etc. The same procedure is applied for the original y-axis and z-axis. Figure 3 illustrates the edge codes for the component envelope.

2.1.3 Component Type: Furthermore, the entire component is classified according to it's shape, particularly, the flat features required. This classification relies on; (1) The cross-sectional profile of the component, and (2) The machining direction for the flat features. Using this classification, prismatic components in BEPPS-GSCAPPP are considered as belonging to one of the three types; (1) *Totally*

Constant Cross-Section component (TCX-SEC), (2) *Partially Constant Cross-Section* component (PCX-SEC), and (3) *Non-Constant Cross-Section* (NCX-SEC).

A component is of totally constant cross section (TCX-SEC) if each of the surfaces that required machining have a constant profile in any plane direction. The partially constant cross section component (PCX-SEC) is a component which, has at least one surface, of those requiring machining with a constant profile in any one plane direction. A component is of non-constant cross section (NCX-SEC) if none of the surfaces requiring machining have a constant profile in any one plane. A component is inputted to the system initially as either a constant or non-constant component. A component of partially constant-cross section is considered as a non-constant component at first. After the system has interactively obtained information about the types of plane surface present each plane surface is then classified as either of constant or non-constant cross-section. Any component containing both is subsequently classified as PCX-SEC by the system.

2.1.4 Machine Availability: The machine tool data in BEPPS-GSCAPPP has been limited to a vertical milling machine, a horizontal milling machine, a pillar drill, a radial drill, a vertical boring machine, a surface grinder, and an internal grinding machine. Actual machine tools have been selected and these in turn impose size constraints on the components that can be machined by the system. The system displays the machine tools (names and codes) so that the planner or production control system are able to delete machines that are currently occupied with other jobs.

2.1.5 Features in BEPPS-GSCAPPP: The system considers a range of machined features that are commonly produced on conventionally machined prismatic parts. The simplified research versions uses 7 features namely; flat surface, pocket, slot, plain hole, stepped hole, countersink and thread.

2.1.5.1 Feature Classification: These seven features are divided into two groups; (1) *Flat* group, and (2) *Cylindrical* group according to the tool geometry and motion required to machine them. The flat group includes faces, pockets, and slots, where as the cylindrical group includes plain holes, stepped holes, countersinks and threads. Each group is then subdivided into Basic and Secondary features as shown in figure 4. The basic feature represents a primary form of the feature and the secondary feature represent deviations from this primary form. This classification has been designed to give a much simpler feature ordering decision logic and to group features requiring the use of the same machine tool type.

2.1.5.2 Feature Data Input: The feature data for each surface that requires machining is inputted to the system interactively via system prompts. Initially the planner is asked to choose one of the three main options after studying the component to be planned. These are; (a) Only flat features are required, (b) Only cylindrical features are required, and (c) Both flat and cylindrical features are required. Once the choice has been made the system displays the range of features within the group for the planner to choose the appropriate feature set. In the case of choice (c), information on the flat features is requested prior to that for cylindrical features. For each feature, the planner is asked for a variety of parameters including; feature code, location, dimensions, tolerances, surface requirements, ...etc. This data is stored in a component data base file that can be retrieved and processed by several modules. At this stage, if the component is constant and the features required for any plane are flat only, the planner is required to input them in a particular order according to the *"Top-To-Bottom"* technique (TOP-TO-BOT).

The TOP-TO-BOT technique is designed to input a feature's information with reference to it's position on the plane. This means that the feature on the top level (greatest z value for x-plane , ...etc.) has priority over the bottom ones. An example of this technique is shown in figure 5. This technique is applied only for flat feature types. If more than one feature exists on the same level, then the feature input sequence is left to the planner's judgement, or alternatively, the *"Scoring"* technique (SCORE) can be applied. The scoring technique is an automatic feature ordering technique designed for all features required on a non-constant cross-section plane surface. This technique is further discussed in the automatic stage.

2.2 Automatic Stage:

Once the input of data has been completed, the system stores the information in a file named by the component number so that it can be either retrieve for modification or be used to generate a process plan automatically. The automatic stage is divided into 8 modules; 1. Raw material selection from stock, 2. Feature recognition and ordering, 3. Operation determination and sequencing, 4. Machine tool selection, 5. Cutting tool selection, 6. Cutting conditions selection, 7. Total time calculation, and 8. Workpiece holding device consideration. This paper concentrates on modules 1 and 2.

2.2.1 Automatic Selection of Raw Material from Stock: The system considers three of the most common materials used for prismatic parts in batch manufacturing factories. Those are; Mild steel, Carbon steel, and Aluminium. Standard shapes and sizes for these materials have been used rather than castings or forgings. GSCAPPP is based on a small batch working shop that only machines components from stock and only keep a small range of standard shaped bars, ...etc. This information is contained within the raw material data base of the system. When during the input stage the shape envelope dimensions are requested, the system checks to establish what if any material allowances are required in order to achieve the tolerances and finishes specified. This is carried out as part of the process planning module and uses expert logic to make the required decision. If any allowances are required, then a fixed allowance is added to the specified dimension.

By using this metal addition technique the system changes the shape envelope of the finished component into the minimum shape envelope of the required raw material and details which surfaces if any are sufficiently accurate to negate machining.

The data base of standard forms assumes at present that each bar, ..etc. is substantially longer than any component that the system can accommodate, hence only X and Y cross-section dimensions are important. A *"best"* fit comparison is carried out in order to match a component's shape envelope with the material X Y dimensions. Basically the component's Length/Width, Length/Depth and Width/Depth are compared against all X Y material dimensions of the stock held. If there is an exact match, the matching algorithm is stopped and the material stock designated as the *"Ideal Form"* i.e. no excess machining is required.

If no ideal form is available, then the data base is searched to find the nearest fits. These are displayed on the screen together with the most appropriate stock size. The most appropriate size is arrived at automatically by taking into account; (a) The minimum volume of excess metal to be removed, (b) The minimum contact area for the machining, and (c) The method of removing the excess metal.

By using these three factors that the choice of the most appropriate stock size is based on a combination of minimum volume and economics. Figure 6 shows the structure of the material selection module.

2.2.2 Automatic Feature Recognition and Ordering Module: As discussed earlier, the SCORE technique is designed to reorder flat and cylindrical features on any non-constant cross-section plane surface as well as cylindrical features on any constant cross-section plane surfaces. In the scoring technique each feature is given a score based on it's *"priority"* for machining. The flat feature group for example typically has priority over the cylindrical group. This will result generally in plans showing *'Mill'* and then *'Drill'* i.e. a hole will not be machined unless the face on which it is located has been completed.

The system retrieves the feature input data from the component data base file and checks the plane surface type. If the plane surface is of non-constant cross-section, firstly the system reorders the flat features and secondly the cylindrical features according to their basic score. If the plane surface is of constant cross-section type, the system reorders only the cylindrical features. Figure 7 shows the structure of the scoring technique.

Once the feature data has been organized into the correct order for processing, the remaining modules are used to automatically determine the required operations and their sequence, the machine tool set, the appropriate cutting tools, cutting conditions and the machining and non-machining times.

CONCLUSION

A generative CAPP system, BEPPS-GSCAPPP has been developed for the automatic planning of prismatic components. It is able to generate a fully documented process planning sheet for the shop floor using automatic planning modules which have been designed for easy modification.

A raw material selection module has been developed that will choose the most appropriate stock size available using decision logic that takes into account the economics of the operation. It is considered that advantages could also be gained by using this module as a stand alone package in a design for manufacture environment.

Two techniques used for feature ordering have been developed and successfully applied to components that can be described using 7 basic feature types. The feature ordering technique (TOP-TO-BOT) is based on the relative height of the flat features present, where as the scoring technique relies on allocating a priority to individual features depending on their basic scores.

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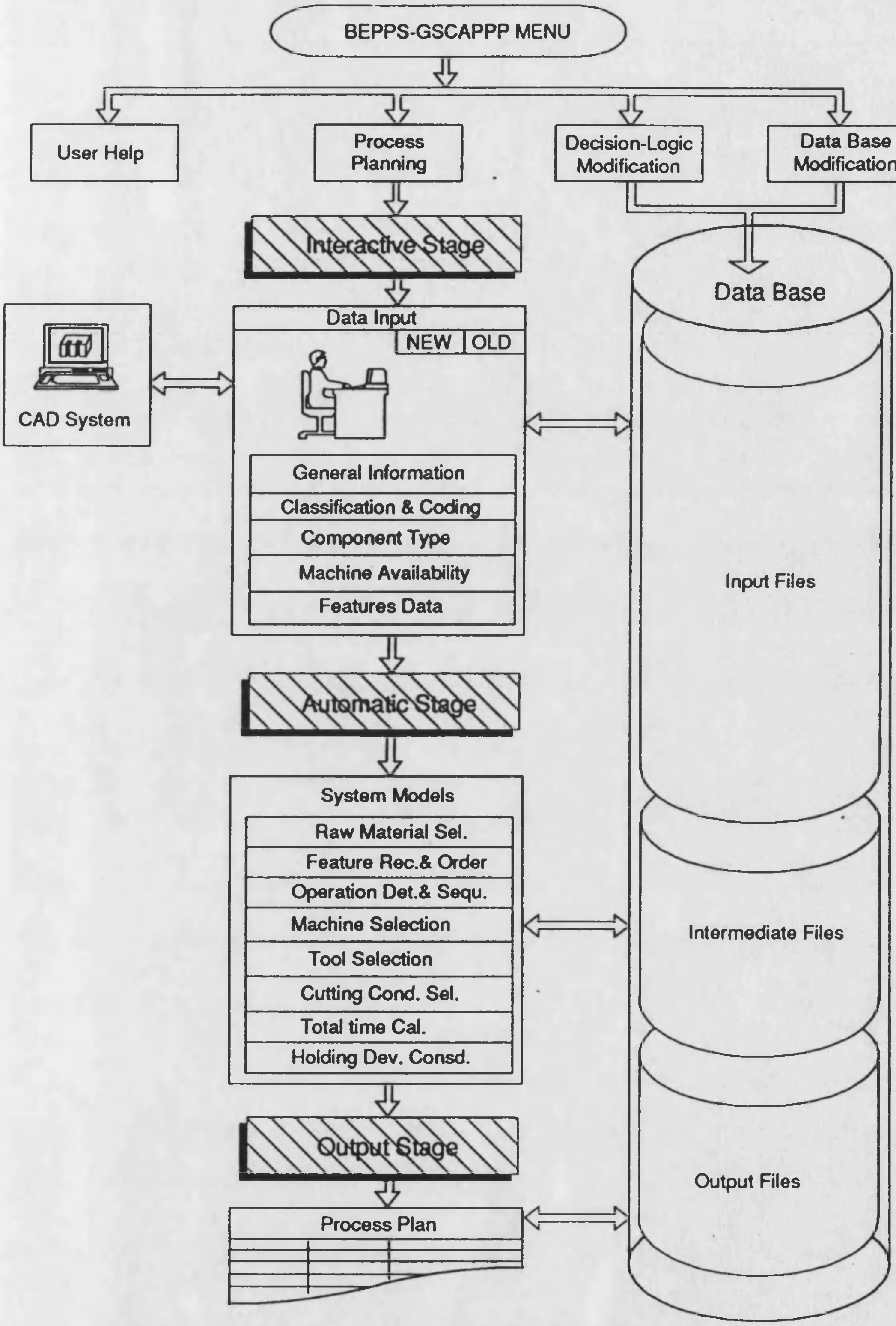

Figure 1: BEPPS-GSCAPPP General Structure.

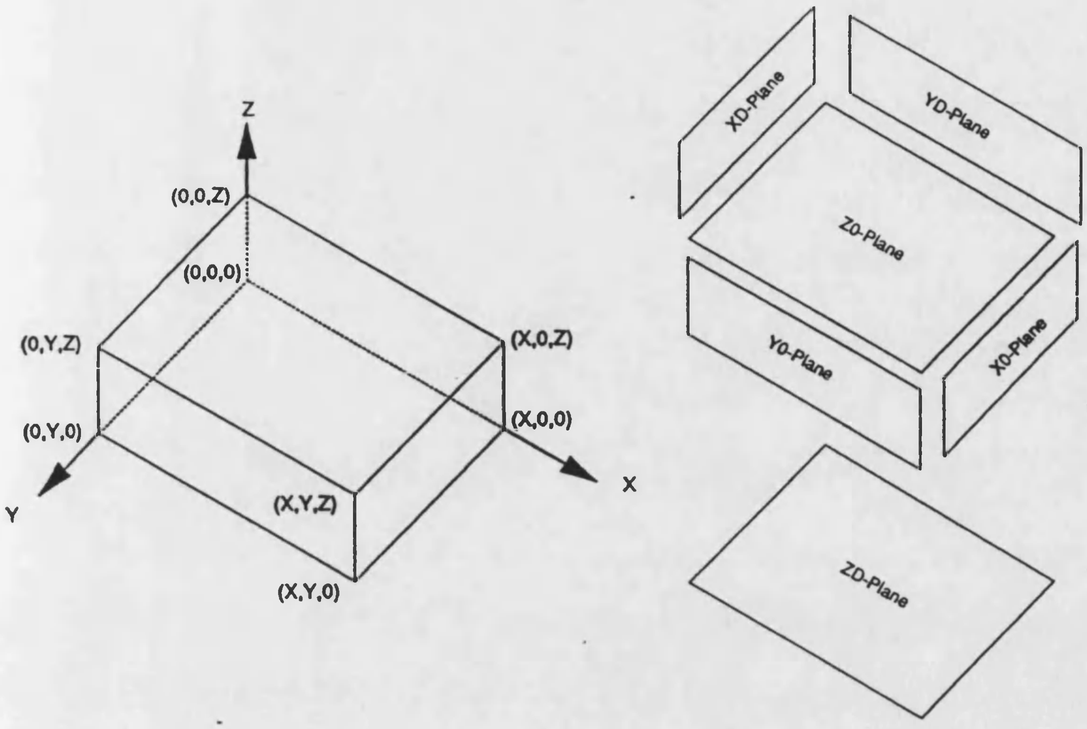

Figure 2: Datum and Opposite Planes of a Component.

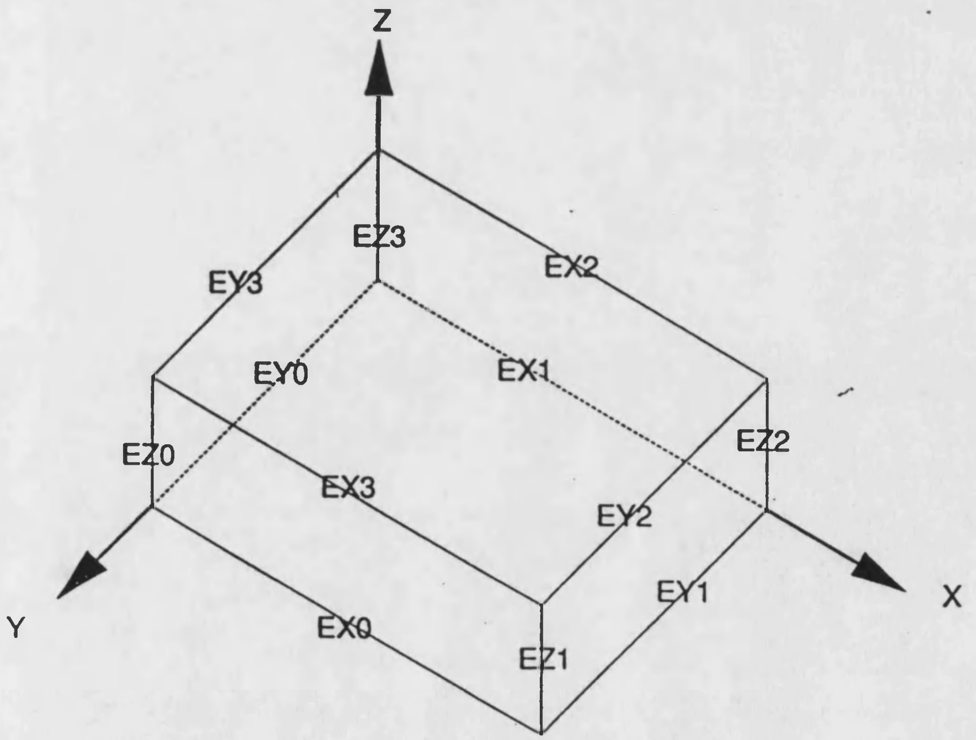

Figure 3: Edge Codes of a Component Shape Envelope.

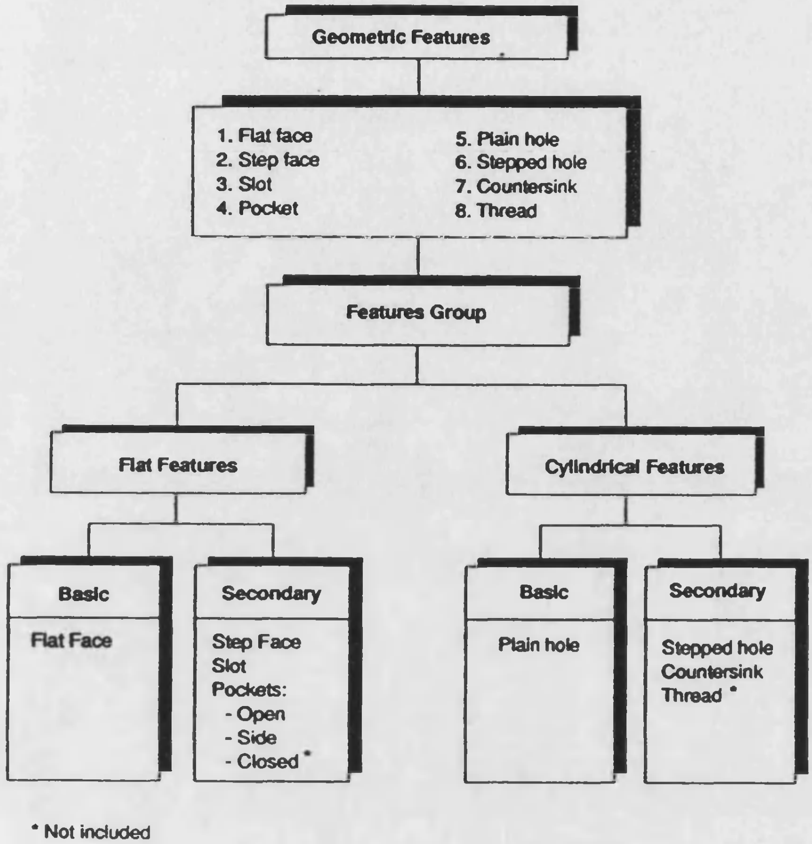

Figure 4: BEPPS-GSCAPPP Features Classification.

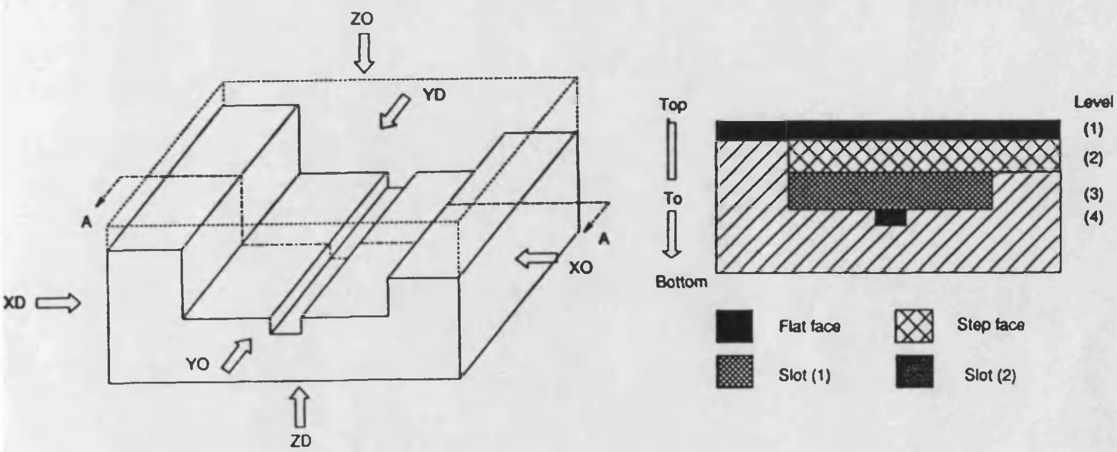

Figure 5: Top-To-Bottom Technique Applied for ZO Plane Surface.

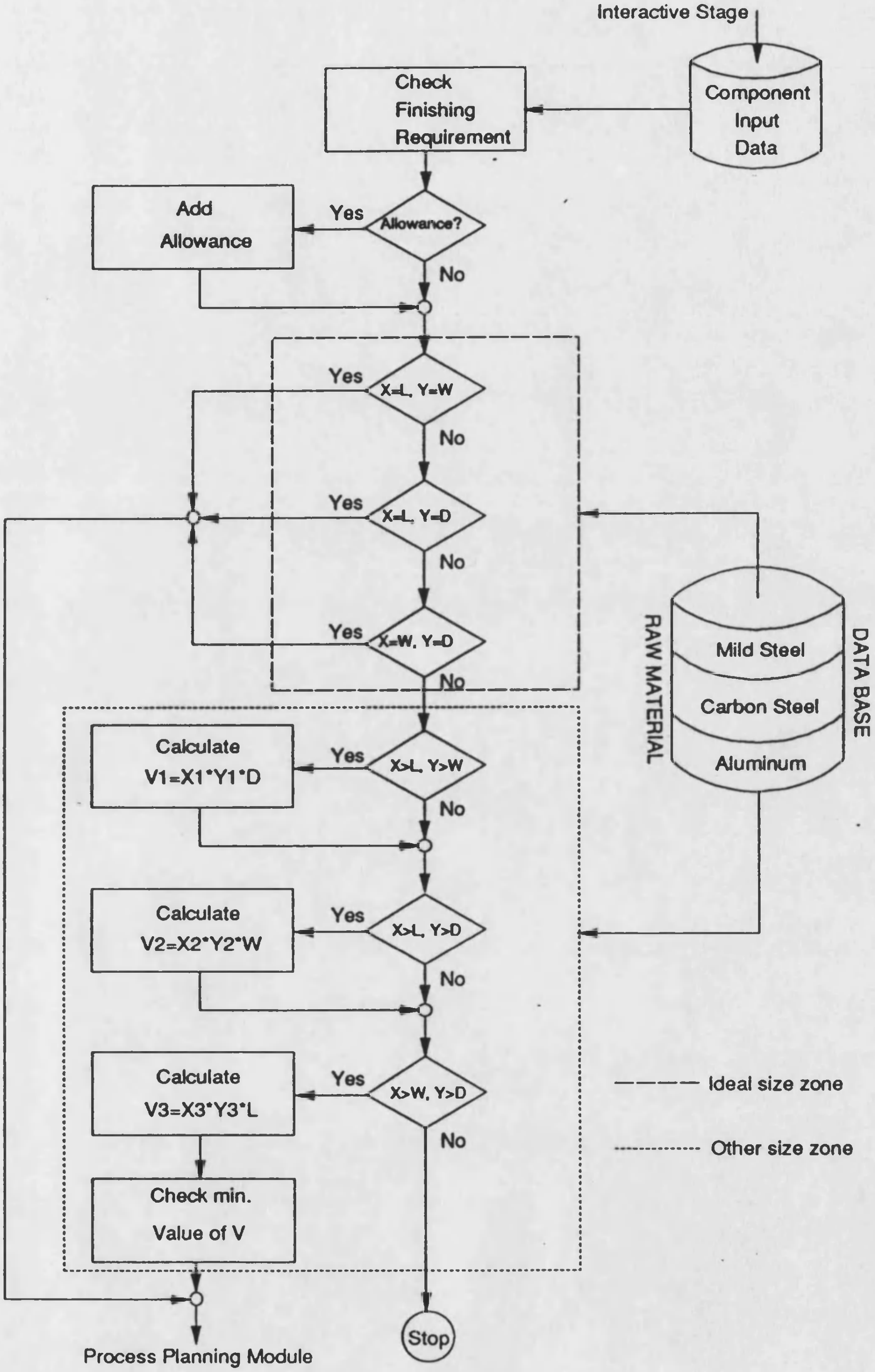

Figure 6: Structure of Raw Material Selection Module.